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Implementation of experimental techniques in ultrasound-driven hydrogen production: A comprehensive review

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A R T I C L E I N F O

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A B S T R A C T

This comprehensive review delves into the utilization of ultrasound for hydrogen generation, emphasizing the key mechanisms and techniques involved. One of the focal points of the study is the exploration of the generation and detection of cavitation bubbles, which are induced by ultrasound waves. An in-depth overview of various experimental setups that employ ultrasound technology for hydrogen production is also provided. A comparative analysis of these setups reveals differences in crucial parameters such as acoustic intensity, liquid temperature, and frequency. These are the key parameters identified as significant determinants affecting the hydrogen yield and efficiency. This review paper also highlights the potential applications of sonohydrogen as a viable energy resource. While challenges such as the high costs of ultrasound equipment and the need for efficient catalysts exist, the inherent benefits make sonohydrogen a compelling subject for future research and development. The study shows that there is no one-size-fits-all approach, accentuating the importance of understanding these parameters for optimizing the process of hydrogen production. Although the technology is primarily in the experimental phase, existing research indicates that the sonohydrogen production holds considerable potential for large-scale applications.

1. Introduction

Hydrogen is a vital energy source for various life forms and processes that span the universe. It has multiple applications including industrial uses, serving as rocket fuel, and being utilized in fuel cells for generating electricity and powering vehicles. Traditionally, this energy is derived from fossil fuels. However, the growing awareness of fossil fuels' negative impacts on the environment such as contributing to air pollution and climate change, emphasizes the need for more sustainable alternatives. Hydrogen can be sustainably produced using ultrasonic technologies.

Ultrasonic technology has found extensive applications across a multitude of fields. In medical treatment, for instance, therapeutic ultrasound is commonly employed for physical therapy, pain management, and promoting tissue healing [1]. Additionally, ultrasonic surgical instruments have revolutionized minimally invasive procedures by enabling precise cutting, coagulation, and tissue removal [2]. Another medical application is lithotripsy, which utilizes focused ultrasonic waves for the fragmentation of kidney stones.

Quality control and precise instrumentation also benefit from ultrasonic technology. Non-destructive testing employs ultrasonic waves to detect flaws or defects in various materials and structures, such as welds, pipelines, and concrete [3]. Thickness gauging techniques measure the thickness of materials like metals, plastics, and glass [4]. Ultrasonic flow meters are employed to accurately determine the flow rate of liquids and gases, adding another dimension to quality control.

In the field of medical imaging, ultrasound imaging stands out as a significant application [5]. It utilizes high-frequency sound waves to generate real-time images of organs, tissues, and blood flow. This proves invaluable for diagnostics and monitoring purposes [6]. Moreover, ultrasonic tech enables welding, cutting (materials like plastics, metals, food), and cleaning (using cavitation) in diverse industrial applications [7,8].

The above-mentioned applications of ultrasound technology are just examples of how this technology continues to advance, opening up new possibilities for innovation and improved processes in multiple industries. Its non-invasive nature, precision, and versatility make it a valuable tool for diverse applications. For example, in industrial cleaning, ultrasound can be effective in cleaning various materials across different industries, such as automotive, electronics, and medicines [9,

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10]. Chen et al. [11] conducted research utilizing ultrasound at a frequency of 20–25 kHz and a maximum power of 1800 W to improve the chemical reactions involved in the remediation and elimination of heavy metals in soil.

Another application of ultrasonic technology lies in water treatment, where it proves to have a remarkable performance [12]. By harnessing high-frequency sound waves, ultrasonic systems efficiently break down organic compounds, eliminate harmful bacteria, and disintegrate suspended particles, providing a potent and environmentally friendly solution for water purification. With its ability to target contaminants at a molecular level and enhance overall water quality, ultrasonic treatment emerges as a promising tool, ensuring the provision of safe and pristine water for countless individuals and communities worldwide. Water treatment involves various processes to ensure the purification and safety of water for various applications [13,14]. Emerging technologies like ultrasound offer innovative approaches to water treatment that can potentially overcome these limitations. Ultrasound technology can enhance process efficiency, reduce energy consumption, and minimize the production of secondary pollutants, making it a promising alternative in the field of water treatment.

In recent years, the extensive utilization of ultrasound is conducted due to its remarkable potential in enabling energy-efficient and environmentally friendly production methods [15]. There are various experimental techniques that are developed to optimize process efficiencies. One of the most widely used techniques is the use of a sonochemical reactor, which consists of a reaction vessel and an ultrasound generator. The ultrasound generator produces sound waves with high frequency that are propagated through the liquid in the reaction vessel, leading to the formation of cavitation bubbles [16].

Ultrasound employs sound waves that have frequencies beyond the range of human perception, which is 20 kHz. Sonochemistry distinguishes ultrasound into two groups: diagnostic waves with high frequency of 2–10 MHz that are predominantly employed in the medical sector, and low-frequency power ultrasound within the range of 20 kHz-2 MHz that creates cavitation in liquids, influencing chemical reactions and procedure. Different applications work at various frequencies [17], such as thermoacoustic refrigeration, thermoacoustic heat engine, sonohydrogen generation, car parking sensors, detecting piping notch, detecting piping corrosion, analysis and monitoring of various food materials, ultrasonic viscometer, food processing preservation and safety, axial and circumferential crack detection of pipes, pipe wall thinning monitoring, piping leakage inspection, measuring wheel/rail contact stresses, mapping of lubricant film thickness along piston skirt and monitoring car engines performance. Fig. 1 shows these applications and their relative ultrasonic frequencies. Reviewing the applications and experiments involving ultrasounds, particularly water treatment along sonohydrogen production can help researchers in the field of mechanical engineering to advance their studies in this area. One related study in this area is the perspective by Rashwan et al. [18] in which an ultrasonic water treatment bath was used to evaluate the effect of CO_2 as a dissolved gas on ultrasonic hydrogen production.

While there is an increasing interest in sonohydrogen production and ultrasound-based water treatment, current reviews lack a comprehensive, comparative analysis of experimental setups. This review aims to fill this gap by providing a systematic evaluation of methodologies, thereby offering a concrete direction for future research.

This article further discusses the field of ultrasound-driven hydrogen generation by providing a holistic view that encompasses a detailed evaluation of ultrasound mechanisms, a comparative review of experimental setups, insights into parameter interactions, and an exploration of sonohydrogen potential. It identifies key research gaps, suggesting areas for future investigation, particularly in scaling up for industrial applications. A major novelty introduced is the proposed method for producing hydrogen sonically using treated water, which outlines a multi-stage process of coagulation, sedimentation, filtration, and disinfection of water before its sonication in specially designed reactor vessels. Additionally, the paper proposes six new sono-reactor configurations, offering new approaches to generate acoustic cavitation bubbles. This review article has several objectives which are detailed below:

- To discuss the mechanisms and techniques involved in the generation and detection of cavitation bubbles caused by utilizing ultrasound generators.

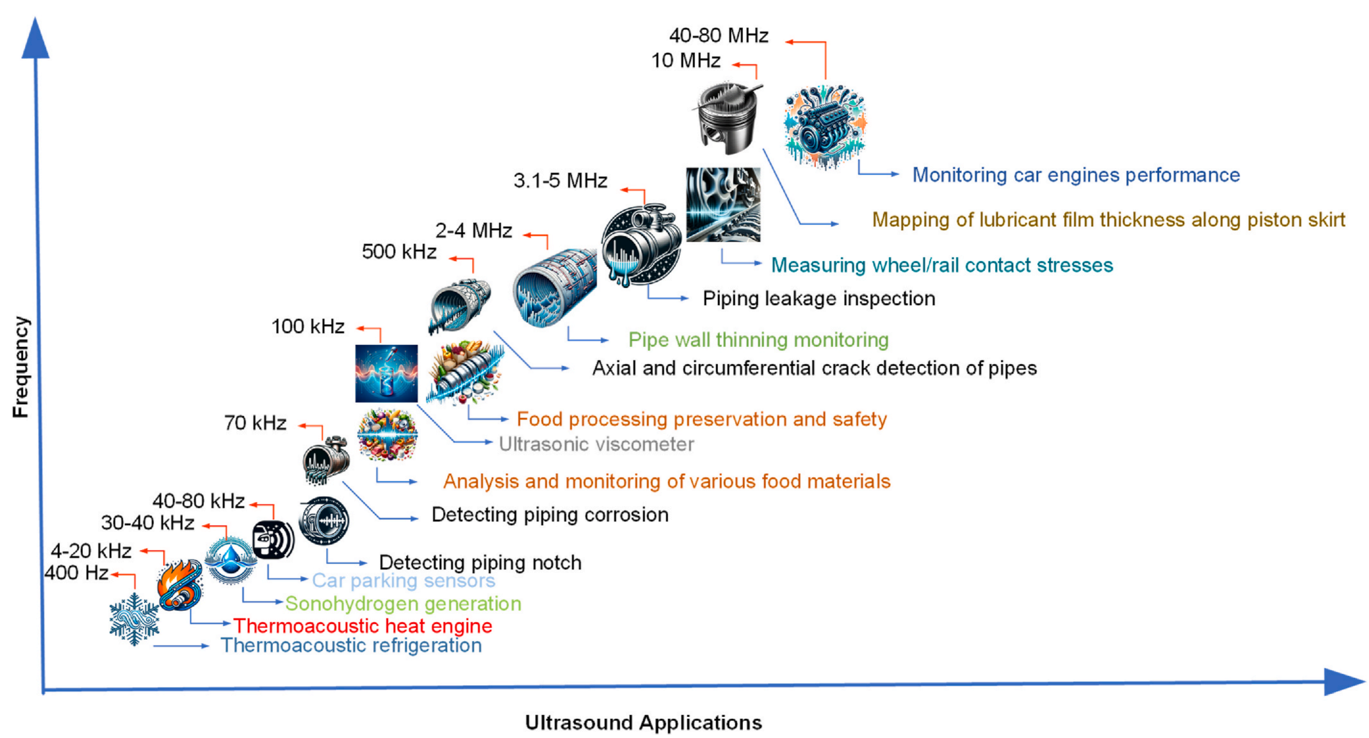

Fig. 1. Ultrasound applications at different ultrasonic frequencies.

- To provide an overview of various experimental setups and applications that utilize ultrasound technology for water treatment and specially hydrogen production.
- To compare the different experimental setups using ultrasound.
- To specifically review the potential and challenges of sonohydrogen production applications.

In the subsequent parts of this article, the content is organized to offer a comprehensive understanding of ultrasound technology in water treatment and hydrogen production. Section two presents a classification of hydrogen production methods. Section three explores the fundamentals and applications of ultrasound-induced cavitation, along with the operational parameters critical for enhancing sonohydrogen production and sonochemical processes. It covers topics, such as acoustic cavitation, bubble dynamics, sono-reactor designs, and the stages of bubble formation and collapse, emphasizing their importance in energy, environmental protection, and sustainability. Section four examines the application of ultrasonic methods in experimental setups for hydrogen production, discussing various sono-reactor configurations. Additionally, this section highlights the significance of integrating water treatment with hydrogen production, proposing an innovative approach that utilizes treated water for sonohydrogen production.. Section five provides a comparative analysis of the experimental setups, offering insights into their relative efficiencies and limitations. Section six discusses the potential and challenges of sonohydrogen production. Section seven presents the conclusion of the study, summarizing the key findings and their implications. Finally, section eight discusses further studies and potential avenues for future research.

2. Hydrogen production methods

Hydrogen, being a versatile and clean energy carrier, holds immense significance in addressing the challenges of climate change and energy sustainability. It offers numerous applications in transportation, industry, and energy storage, making efficient and sustainable methods of hydrogen production essential.

There are several methods for hydrogen production, including electrochemical, thermochemical, thermal, chemical, biological, photonic, and sonic approaches (see Fig. 2):

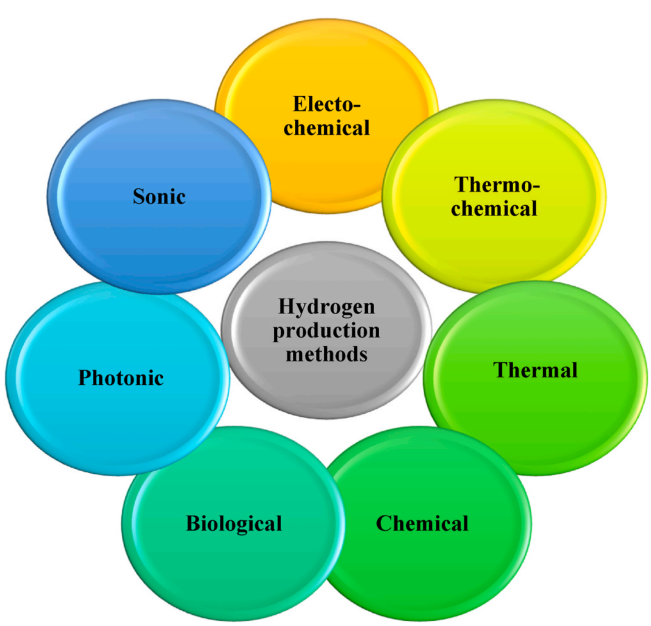

Fig. 2. Some common hydrogen production methods.

1) Electrochemical Methods: This category includes processes like electrolysis, where an electric current is used to split water into hydrogen and oxygen. This method is particularly attractive when the electricity used is sourced from renewable energies, making the hydrogen production zero-emission.

The process of electrochemical water decomposition involves specific reactions at the anode and cathode, each with its own reversible potential in a water electrolysis cell. These reactions are described as follows [19]: At the anode, water undergoes oxidation:

$$H_2O \rightarrow 2H^+ + 1/2O_2 + 2e^- \tag{4}$$

At the cathode, hydrogen ions are reduced:

$$2H^+ + 2e^- \rightarrow H_2 \tag{5}$$

The overall reaction for water electrolysis is:

$$H_2O \rightarrow H_2 + 1/2O_2 \tag{6}$$

2) Thermochemical Methods: These methods involve using heat to induce chemical reactions that produce hydrogen. Common thermochemical processes include steam reforming, where high-temperature steam reacts with a hydrocarbon fuel to produce hydrogen, and gasification, where materials like coal or biomass are converted into hydrogen and other gases at high temperatures. This method of hydrogen production involves steam methane reforming (SMR), which is recognized as one of the most commonly employed techniques for generating hydrogen from gaseous substances like methane, ethanol, and methanol.

An SMR process consists of two key reactions: methane reforming and the water gas shift (WGS) [20]. These reactions can be represented as follows [21]:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2}$$

These equations collectively represent the SMR process. An alternative method for syngas production is the dry methane reforming (DMR) process, which uses carbon dioxide as a reactant. In this process, methane reacts with carbon dioxide as shown in the following reaction:

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \tag{3}$$

Both of these reaction systems, SMR and DMR, operate at high temperatures (around 1000 °C) to ensure efficient methane conversion. The operational pressures required for SMR and DMR reactors are 34 bar and 4 bar, respectively.

(3) Thermal Methods: Thermolysis, or thermal hydrogen production, employs high heat to split water into hydrogen and oxygen. To reach substantial levels of dissociation, temperatures exceeding 2500 K are necessary. The main difficulties with this method include effectively separating the hydrogen and oxygen gases and handling the high energy demands needed to maintain these temperatures.

(4) Chemical Methods: Hydrogen production through chemical means is based on chemical reactions, often eliminating the requirement for external energy sources. An example includes metals reacting with acids to generate hydrogen. The reactions are driven by the chemical energy present in the materials, often resulting in exothermic processes that emit energy. The effectiveness of these chemical techniques can greatly differ based on the reactions and materials used. Nonetheless, they are generally less scalable compared to electrochemical or thermochemical methods, making them more appropriate for smaller operations

or particular applications. The environmental effects of producing hydrogen chemically vary significantly and depend on the chemicals used and their origins. Some processes may generate toxic waste or use materials with sustainability issues, underscoring the importance of thoughtful selection of chemical processes for hydrogen generation.

(5) Biological Methods: Biological hydrogen production is emerging as a promising renewable energy technology, utilizing the metabolic activities of microorganisms such as algae and bacteria to produce hydrogen. This approach encompasses three primary techniques: biophotolysis, photo fermentation, and dark fermentation. In biophotolysis, algae or cyanobacteria exploit sunlight to break down water molecules into hydrogen and oxygen, harnessing solar energy through their photosynthetic machinery to generate the necessary high-energy electrons for water splitting. This method benefits from the abundant availability of sunlight and water. Photo fermentation differs by not splitting water but by using sunlight to enable certain bacteria, like purple non-sulfur bacteria, to transform organic compounds into hydrogen and carbon dioxide, offering flexibility with the organic materials used and the possibility of integration with waste treatment. Dark fermentation, on the other hand, operates without sunlight, relying on bacteria to convert organic matter into hydrogen in the dark. This process is notable for its capacity to utilize a broad spectrum of biodegradable waste as feedstock, presenting a sustainable and cost-effective hydrogen production route that aligns well with waste reduction and recycling initiatives.

(6) Photonic Methods: Photonic hydrogen production methods utilize light energy, particularly from the sun, to catalyze the chemical reactions required to decompose water into hydrogen and oxygen. This technique uniquely employs photons directly in the hydrogen generation process, eliminating the need for an intermediate step of electrical energy conversion. Central to this approach are photoactive materials that capture sunlight to create electron-hole pairs, initiating redox reactions that separate water molecules. A significant hurdle in this method is finding efficient and durable photocatalysts capable of withstanding a wide range of solar radiation and aquatic environments without breaking down. Photonic strategies offer a sustainable and eco-friendly avenue for hydrogen production, tapping into the vast and inexhaustible supply of solar energy.

(7) Sonic Methods: Sonic methods for hydrogen production utilize ultrasound technology. This approach has demonstrated that hydrogen can be generated by applying ultrasonic waves to liquid water. In contrast to non-renewable energy sources, hydrogen can be produced indefinitely through a straightforward process of extracting it from water molecules. This approach is known as the sonohydrogen method.

Sonohydrogen production is an innovative application of ultrasonic technology. It has recently gained attention in hydrogen energy research. Sonohydrogen production utilizes ultrasound and cavitation to induce chemical reactions in a liquid medium. The process involves the rapid formation and collapse of tiny bubbles, creating intense localized pressures and temperatures. This facilitates the dissociation of water molecules into hydrogen and oxygen [22]. Compared to traditional methods, sonohydrogen production offers several advantages. Sonohydrogen generation involves the following reactions [23]:

$$H_2O + h_{sound} \rightarrow OH + H \quad (7)$$

$$OH + H \rightarrow H_2 + O \quad (8)$$

where h is the energy added.

In summary, the ultrasound hydrogen production methods offer a diverse range of operational principles, each leveraging unique aspects of ultrasound technology to facilitate hydrogen generation. These methods either enhance traditional approaches or introduce innovative pathways, thereby contributing to the advancement of sustainable hydrogen production. Conventional methods of hydrogen production, such as steam methane reforming (SMR) and electrolysis, face limitations and challenges that hinder their large-scale implementation (see Table 1). These methods often require high energy inputs, typically sourced from fossil fuels, and contribute to greenhouse gas emissions [24]. The infrastructure required for hydrogen production, storage, and transportation also poses logistical challenges. To overcome these limitations, alternative approaches like hydrogen production with ultrasound technology have emerged as promising solutions.

3. Ultrasound-induced cavitation

This section delves into the mechanisms and techniques involved in generating and detecting cavitation bubbles. It encompasses a detailed analysis of ultrasound generators, their principles, and operation, as well as the intriguing phenomenon of acoustic cavitation and the dynamics of bubbles. Additionally, the research explores different methods for effectively detecting and understanding cavitation bubbles, providing valuable insights into this fascinating area of study.

3.1. Operational conditions

The operational parameters for ultrasound-assist experiment can vary depending on the specific setup and goals (e.g., hydrogen production), but here are some key parameters to consider:

(1) Ultrasound Frequency: The choice of ultrasound frequency is crucial. Frequencies typically used for sonohydrogen experiments range from 20 kHz to several MHz. Specific frequency can influence the efficiency of hydrogen production and bubble formation.

(2) Ultrasound Intensity: The intensity of the ultrasound waves is another important parameter. It can be adjusted by controlling the power of the ultrasound transducer. Higher intensity can lead to more efficient hydrogen production but can also cause cavitation and potential damage to the equipment.

(3) Temperature: The temperature of the water in the experiment can impact the rate of hydrogen production. Typically, the water is maintained at a constant temperature using a water bath or a temperature control system.

(4) Reaction Vessel: The vessel used for the experiment should be designed to withstand the high-intensity ultrasound waves. It should also be sealed to prevent the escape of hydrogen gas.

(5) Gas Collection System: You will need a system to collect the generated hydrogen gas. This can include gas syringes, gas bags, or other collection devices. It's important to measure the volume of gas produced accurately.

(6) Catalysts or Additives: Some sonohydrogen experiments may involve the use of catalysts or additives to enhance the hydrogen production process. The type and concentration of these substances can vary based on the experiment's objectives.

(7) Sonication Time: The duration of sonication (the time during which ultrasound is applied to the water) is a critical parameter. It can affect the yield of hydrogen gas, so it needs to be controlled and monitored.

(8) Water Quality: The quality of the water used in the experiment can also impact the results. Deionized or distilled water is often preferred to minimize impurities.

(9) Number of Sonotrodes: The number of sonotrodes used in the experiment can greatly impact the distribution and intensity of ultrasound waves within the reaction vessel. Using multiple sonotrodes can lead to a more uniform sonication, potentially increasing the efficiency of hydrogen production. However, it

Table 1
Comparative analysis of hydrogen production methods: conventional and emerging technologies.

Criteria	Electrochemical Methods	Thermochemical Methods	Thermal Methods	Chemical Methods	Biological Methods	Photonic Methods	Sonic Methods
Principle	Uses electric current to split water	Uses heat to induce chemical reactions for hydrogen production	Uses high temperatures to split water	Based on chemical reactions without external energy	Utilizes microorganisms to produce hydrogen	Utilizes sunlight to catalyze water decomposition	Uses ultrasound waves to generate hydrogen from water
Energy Efficiency	High with renewable electricity	High, requires high temperatures	High, but requires extremely high temperatures	Variable, depends on chemical reactions	Variable, dependent on biological processes	High, direct use of solar energy	Potentially high due to direct energy conversion
Energy Source	Renewable or fossil-based electricity	Fossil fuels, biomass	High thermal energy, often from non-renewable sources	Chemical energy from reactants	Solar energy (biophotolysis), organic matter	Solar energy	Electrical energy for ultrasound
CO_2 Emissions	Low with renewables, otherwise high	Moderate to high, depends on feedstock	Low to negligible, but energy source matters	Depends on chemicals used	Low, uses renewable sources or waste	Low, uses solar energy	Low, if powered by renewable energy
Infrastructure Needs	Investment in electrolysis plants	Established for SMR, developing for others	High for temperature management systems	Depends on scale and chemicals used	Developing, requires bioreactors or similar	Developing, needs photocatalytic systems	Emerging, ultrasound equipment
Cost	Decreasing with technology, but initially high	Moderate to high, depending on process	High, due to energy requirements	Variable, often lower but scale-limited	Potentially low with waste materials	High, due to technology development	Expected to have lower operational costs; capital costs uncertain
Scalability	Scalable with renewable energy integration	Scalable, especially SMR	Limited by high energy demands	Limited by chemical sources and safety	Potentially scalable with bioreactor advancements	Depends on photocatalyst development	Potential for scalability with advances in technology
Environmental Impact	Low with renewable energy	Depends on feedstock; generally moderate	Low direct emissions, but depends on energy source	Depends on chemicals and processes	Low, uses waste or renewable resources	Low, solar energy is clean	Potentially lower with reduced energy needs and emissions

also requires careful alignment and calibration to ensure optimal performance and to avoid interference patterns that could reduce the effectiveness of the ultrasound.

3.2. Effects of ultrasonic waves on liquids

When ultrasonic waves pass through a liquid, two significant effects take place: (i) acoustic streaming, which is a fluid flow that does not depend on time, and (ii) acoustic cavitation, which refers to the formation and collapse of gas-filled cavities in the liquid. These two effects can happen simultaneously depending on the electrochemical reactor's composition, shape, and size. Low-frequency ultrasound which typically functions at frequencies below 100 kHz, exposure causes the liquid to form cavitation bubbles, which then violently collapse, generating high-energy "hotspots" within the fluid. This collapse can create pressures and temperatures up to 2000 atm and 5000 °C, respectively [25].

3.3. Cavitation bubble formation process

Understanding the formation and behavior of cavitation bubbles is crucial for optimizing various applications that leverage ultrasound-induced cavitation, including sonohydrogen production. The process of cavitation bubble formation involves a series of complex physical phenomena, which can be categorized into several key stages such as (a) nucleation, (b) bubble growth, (c) bubble stability, (d) bubble collapse, and (e) Post-Collapse Phenomena (see Fig. 3).

3.3.1. Bubble nucleation

Nucleation is the initial stage of cavitation bubble formation, where tiny gas-filled cavities emerge within the liquid. This process can be initiated by impurities, pre-existing air bubbles, or areas of low pressure in the fluid. The nucleation process is governed by the liquid's properties, such as viscosity (μ) and surface tension (σ), and external factors, such as temperature (T) and pressure (P). The presence of nanobubbles, which are typically a mixture of water vapor and air, plays a significant role in reducing the cavitation threshold, making nucleation easier under certain conditions.

Nucleation is also significantly influenced by the acoustic properties of the ultrasound used in the process. The frequency and intensity of the ultrasound waves can alter the nucleation rate, as they affect the pressure variations within the liquid. Higher frequencies may lead to a greater number of smaller nucleation sites, while lower frequencies might result in fewer but larger cavitation bubbles. Additionally, the interaction between ultrasound waves and the liquid's thermal

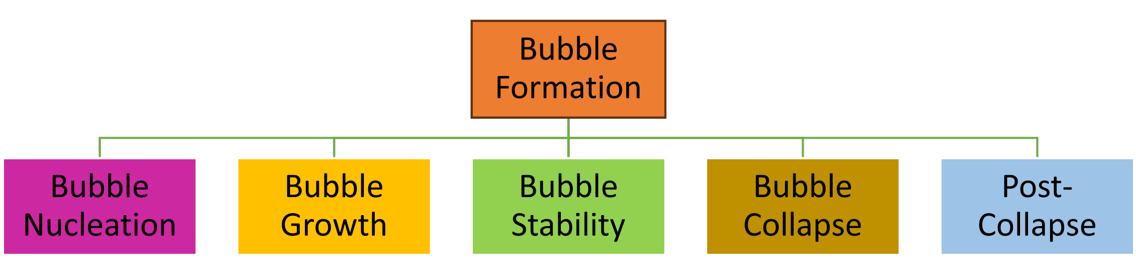

Fig. 3. Some important aspects of cavitation bubble formation.

properties can lead to localized heating, which further affects the nucleation process. This interplay between acoustic and thermal effects is a critical area of study for optimizing sonohydrogen production.

Furthermore, the heterogeneous nature of nucleation, where cavitation occurs preferentially at certain sites within the liquid, is an important aspect. These sites can be natural impurities, introduced particles, or even microstructural irregularities on the container's surface. Understanding the characteristics of these nucleation sites, such as their material composition, size, and distribution, can provide insights into controlling the nucleation process. This control is essential for achieving a consistent and efficient cavitation process, which is vital for applications in hydrogen production and water treatment. By manipulating these nucleation sites, it may be possible to tailor the cavitation process to specific needs, enhancing both the yield and efficiency of the sonohydrogen production.

3.3.2. Bubble growth

After nucleation, the bubble enters the growth phase under the influence of ultrasound waves. The acoustic cycle's low-pressure phase causes the bubble to expand as the internal gas pressure ($P_{internal}$) falls below the surrounding liquid pressure (P_{liquid}). This expansion can be described by the Rayleigh-Plesset equation as below:

$$\mathrm{R}\ddot{\mathrm{R}}+\frac{3}{2}\dot{\mathrm{R}}^{2}=\frac{\mathrm{P}_{\text{internal}}-\mathrm{P}_{\text{liquid}-\frac{2\sigma}{\mathrm{R}}}}{\rho} \tag{9}$$

where R is the bubble radius, and ρ is the liquid density. During this phase, bubbles may coalesce, forming larger bubbles.

During the growth phase, the dynamics of bubble expansion are also influenced by factors such as the gas content within the bubble and the physicochemical properties of the liquid. The type of gas trapped inside the bubble, whether it is air, vapor, or a mixture, can significantly affect the growth dynamics. Gases with higher solubility in the liquid tend to dissolve more quickly, potentially limiting bubble growth. Conversely, gases with lower solubility can promote larger bubble sizes. Additionally, the presence of dissolved gases in the liquid can lead to a diffusion-driven growth, where gas molecules diffuse into the bubble, causing it to expand.

The interaction between adjacent bubbles is another critical factor during the growth phase. As bubbles grow, they can attract each other due to fluid dynamics and acoustic forces, leading to coalescence. This coalescence results in larger, but fewer, bubbles within the liquid. The behavior of these coalescing bubbles is complex and can significantly impact the efficiency of cavitation processes. In sonohydrogen production, for instance, the size and distribution of these bubbles can influence the rate and yield of hydrogen generation. Understanding and controlling this aspect of bubble dynamics could lead to more efficient and controlled cavitation processes, enhancing the effectiveness of applications like sonohydrogen production and water treatment.

3.3.3. Bubble stability

Not all bubbles proceed to collapse. Some achieve a stable size, influenced by factors like acoustic pressure, liquid viscosity, and gas diffusion. The stability of these bubbles is crucial in determining their lifetime in the fluid. The Blake threshold concept provides a criterion for the minimum pressure required for a bubble to grow explosively. It is given by Ref. [17]:

$$P_B=P_0-P_v+\frac{4_\sigma}{3R_{crit}} \tag{10}$$

$$R_{crit}=\sqrt{\frac{3{R_0}^3}{2_\sigma}\left(P_0+\frac{2_\sigma}{R_0}-P_v\right)} \tag{11}$$

where P_B is the Blake threshold, P_0 is the ambient pressure, R is the bubble radius, and P_v is the vapor pressure.

The hydrostatic pressure surrounding the bubble is typically 1 bar, while the vapor pressure amounts to 2.33 kPa. Surface tension, symbolized as σ, is the force per unit length acting perpendicular to a line on a liquid surface, with a value of 0.0728 N/m for water.

The stability of a bubble is also influenced by the phenomenon of gas diffusion across the bubble boundary. Gas diffusion, both into and out of the bubble, is governed by the concentration gradient of the gas in the liquid and the gas within the bubble. In scenarios where the internal gas pressure is lower than the gas concentration in the surrounding liquid, gas molecules diffuse into the bubble, stabilizing it against collapse. Conversely, if the internal pressure is higher, gas diffuses out, potentially leading to bubble shrinkage and collapse. This dynamic equilibrium plays a crucial role in determining the final stable size of the bubble and its lifetime in the fluid.

Moreover, the oscillatory nature of the acoustic field in ultrasound applications adds another layer of complexity to bubble stability. The periodic changes in pressure due to the acoustic waves can cause bubbles to undergo repeated cycles of expansion and contraction, known as pulsation. These pulsations can stabilize the bubble by balancing the forces acting on it, thereby preventing its premature collapse. This aspect is particularly important in applications like sonohydrogen production, where the efficiency of the process can be significantly influenced by the stability and pulsation behavior of the cavitation bubbles.

3.3.4. Bubble collapse

The high-pressure phase of the acoustic cycle leads to the bubble's collapse, generating extreme temperatures and pressures. This collapse can be characterized by a rapid decrease in bubble size, leading to a localized "hotspot" in the liquid. The conditions during collapse are critical for sonochemical reactions, such as sonohydrogen production. The collapse phase can be described by the Keller-Miksis equation, which accounts for the compressibility of the liquid and the bubble dynamics according to Refs. [26–28]:

$$\rho\left[\left(1-\frac{\dot{R}}{C}\right)R\ddot{R}+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3C}\right)\right]=\frac{1}{\rho_L}\left(1+\frac{\dot{R}}{C}+\frac{R}{C}\frac{d}{dt}\right)\left[p-\frac{4\mu LR+_{2\sigma}}{R}-p_0-p_A\sin(2\pi ft)\right] \tag{12}$$

where p_A is acoustic pressure amplitude, f is the ultrasonic frequency, μ is the liquid viscosity, σ is the surface tension, p_∞ represents the static pressure of the surrounding medium in which the bubble is located, P is pressure inside the bubble, C is sound speed, ρ_L is liquid medium density, and R is R concerning time.

When the thermal effect is investigated, the value of P can be calculated by the following equation:

$$\mathrm{P}=\frac{\mathrm{N_g KT}}{\frac{4}{3}\pi\mathrm{R(t)}^3-\mathrm{N_g B}} \tag{13}$$

where B is the molecular co-volume of the gas inside the bubble, K is the Boltzman constant (1.38 × 10–23 J/K) [29], and Ng is the total number of the gas molecules.

The process of bubble collapse is not only a rapid contraction but also a highly energetic event. As the bubble shrinks, the gas inside it is adiabatically compressed, leading to a significant increase in temperature and pressure. This phenomenon is responsible for the generation of shock waves and microjets within the liquid, which are key to sonochemical reactions and mechanical effects in the fluid. In the context of sonohydrogen production, these extreme conditions during the collapse phase facilitate the dissociation of water molecules, leading to hydrogen generation.

Additionally, the asymmetry in bubble collapse plays a crucial role in the dynamics of this phase. In a non-uniform acoustic field or near a solid boundary, the collapse can become asymmetric, leading to the

formation of high-speed microjets directed towards the nearest surface. These microjets contribute to increased shear forces and enhanced mixing in the liquid, which can be beneficial for both sonochemical reactions and mechanical applications like cleaning or mixing. Understanding the factors that influence the symmetry of bubble collapse, such as the proximity to solid boundaries and the distribution of acoustic pressure, is essential for optimizing the efficiency of cavitation-based processes.

Moreover, the repetitive nature of the collapse in an acoustic field leads to a phenomenon known as cavitation erosion. Over time, the repeated collapses can cause physical wear and damage to nearby surfaces, including the walls of the reactor or any immersed equipment. This aspect is particularly important from a design and material selection standpoint for sonohydrogen reactors and other cavitation-based systems, where minimizing erosion can extend the lifespan and efficiency of the equipment.

3.3.5. Post-collapse phenomena

Following collapse, a bubble may dissolve or undergo a series of rebounds, leading to secondary cavitation. These secondary bubbles interact with the ultrasound waves, repeating the growth and collapse cycle. The dynamics of this phase are complex and depend on the initial conditions of the bubble and the surrounding fluid.

The post-collapse phase is also characterized by a range of complex behaviors that are influenced by the energy and dynamics of the preceding collapse. One such phenomenon is the formation of shock waves, which radiate outward from the point of collapse. These shock waves can contribute to the nucleation of new bubbles in the surrounding fluid, thereby initiating a new cycle of cavitation. This process is particularly relevant in sonochemical applications, where the generation and propagation of shock waves can enhance chemical reactions and improve mixing in the fluid.

Furthermore, the interaction between rebounding bubbles and the surrounding fluid can lead to significant fluid dynamics effects, such as microstreaming and increased turbulence. These effects can enhance mass transfer in the fluid, which is beneficial for processes like water treatment and chemical synthesis. Understanding and controlling these post-collapse fluid dynamics can lead to more efficient design and operation of cavitation-based systems.

Understanding these stages can provide valuable insights into the control and optimization of sonohydrogen production and other applications. The stability, size, and frequency of cavitation bubbles can be manipulated by adjusting various parameters such as ultrasound frequency, acoustic pressure, and reactor geometry, thereby affecting the efficiency and yield of the sonochemical processes involved.

3.4. Detection methods for cavitation bubbles

Cavitation bubbles are phenomena that occur in various fields, including industrial processes, and marine applications. Understanding and detecting cavitation are crucial for optimizing these processes and ensuring their safety and efficiency.

According to the study of Wu et al. [31] there are three different acoustic methods for characterizing cavitation based on how the detector collects signals from the cavitation field. These methods are active cavitation detection (ACD), passive cavitation detection (PCD), and self-sensing cavitation detection (SSCD), which are depicted in Fig. 4. In ACD, cavitation is detected using backscattering technology. This involves a transducer that sends ultrasonic waves into the cavitation field, and another transducer or the same one receives the ultrasonic reflection from the cavitation bubbles. On the other hand, PCD is based on analyzing the spectrum of cavitation noise that is emitted by cavitation bubbles. In cases where conventional measuring sensors like hydrophones cannot be placed in high-temperature liquids, such as during ultrasonic processing of molten metal, SSCD can be used for process monitoring. This involves using high-temperature measurement sensors like a high-temperature cavitometer or making use of the existing processing transducers in the work medium.

3.5. Acoustic cavitation: sono-reactor designs and bubble phenomena

Cavitation is an intriguing occurrence that takes place when alterations in pressure lead to the formation of small air bubbles within a liquid, such as water. This phenomenon typically arises in turbulent fluid motion, characterized by erratic changes in pressure and flow velocity. Unlike the smooth and undisturbed flow of laminar motion, cavitation arises from a reduction in pressure, resulting in the boiling of the liquid and the subsequent formation of bubbles. These bubbles swiftly emerge but are short-lived due to the significant pressure difference between the surrounding fluid and the virtual vacuum inside the bubble. Consequently, they collapse almost instantaneously, generating a small explosion upon interaction with the passing flow. When this

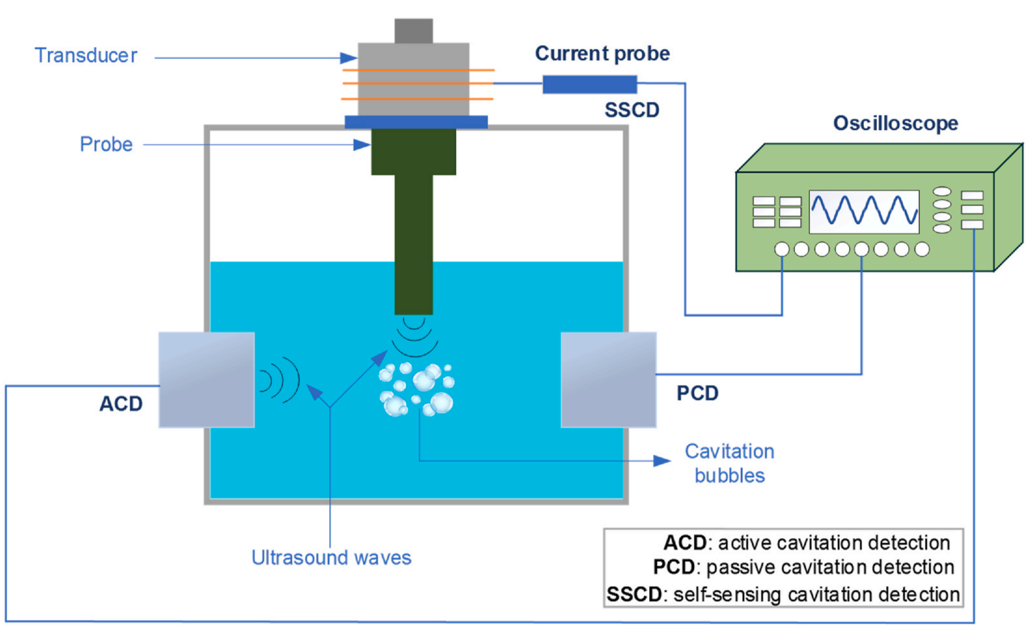

Fig. 4. Schematic representation of three distinct acoustic methods utilized for the characterization of cavitation.

process repeats, it can have detrimental effects, compromising the integrity of the material in contact with the fluid.

Acoustic cavitation, the formation of bubbles in a liquid by sound waves, is typically achieved using devices called sono-reactors. Fig. 5 discusses ten main structures of sonoreactors available in the literature (from Type A to Type J).

Generally, some setups employ a plate transducer, while others use an ultrasonic transducer probe that is placed inside the liquid vessel. Some setups use a cooling bath or a chiller to lower the temperature of the solution. The transducer plates can be placed under the cooling bath or inside it [30]. A comparison is provided in Table 2 and the applications of these configurations are discussed in sections 4 and 5 of this study.

Furthermore, as depicted in Fig. 6, the current authors have proposed six new sono-reactor configurations for generating acoustic cavitation bubbles. These configurations pave the way for future research utilizing these newly introduced designs.

The choice between configurations depends on specific process requirements, including the desired efficiency of bubble generation and dispersion, maintenance considerations, and the complexity of the setup. Each configuration has its unique advantages and disadvantages, and the selection would be based on which factors are most critical for the specific application at hand. For instance, for sonohydrogen production multiple configurations might be tested under varying conditions to determine the most effective setup.

The dynamics of bubbles, especially in acoustic cavitation, are governed by a complex interplay of various factors. Acoustic parameters play a crucial role, where the frequency and intensity of sound waves directly influence bubble size and the energy dynamics within the bubbles. The properties of the fluid in which the bubbles are formed are also critical. Viscosity, for instance, can dampen bubble motion and affect the rate of collapse, while surface tension impacts bubble stability and formation. The density of the fluid influences the buoyancy and movement of the bubbles. Temperature is another vital factor; higher temperatures typically reduce the fluid's viscosity and surface tension, altering bubble behavior. Ambient pressure is equally important, as it determines the onset of cavitation and the intensity of bubble collapse. Additionally, the gas content in the liquid, including the types and amounts of dissolved gases, can significantly affect bubble nucleation and growth. Finally, the geometrical constraints of the system, such as the shape and size of the container or reactor, can modify how bubbles interact with their environment. It is worth noting that acoustic cavitation bubbles differ from Taylor bubbles. Taylor bubbles are influenced by physical tube properties and gravity, while acoustic cavitation bubbles are governed by sound wave dynamics and fluid characteristics (see Table 3).

In the context of acoustic cavitation, the Weber number may help predict whether a bubble will undergo stable oscillations or break up. The Weber number is a dimensionless number that gives an indication of the relative importance of the fluid's inertia compared to its surface tension. It is calculated using the formula:

$$We = \frac{\rho L v^2}{\sigma} \tag{14}$$

where ρ is the density of the fluid, L is the characteristic length (typically the diameter of the bubble), v is the velocity of the fluid relative to the object, and σ is the surface tension of the fluid.

In bubble dynamics, the Bond number helps in understanding the shape of the bubble and its rise behavior in the fluid. The Bond number measures the influence of gravitational forces compared to surface tension forces. It is calculated using the formula:

$$Bo = \frac{\Delta\rho g L^2}{\sigma} \tag{15}$$

where $\Delta\rho$ is the difference in density between the two phases (liquid and gas), g is the acceleration due to gravity, L is the characteristic length.

To calculate the Weber and Bond numbers for bubbles, one must consider the relevant physical properties of the fluid (density, surface tension), the size of the bubbles, and the conditions under which they are formed, such as the relative velocity in the case of the Weber number. These values can vary significantly based on the experimental setup, the type of liquid, and the conditions under which cavitation is induced. Furthermore, the Rayleigh-Plesset equation (equation (9)) is relevant for describing the radial dynamics of these oscillating bubbles in an incompressible fluid. This equation helps in understanding how bubble size, pressure variations, and fluid properties influence their behavior. Factors such as fluid viscosity, surface tension, temperature, and acoustic parameters (frequency, intensity) play a significant role in bubble formation, growth, and collapse. This understanding is crucial for optimizing sonochemical processes in applications like sonohydrogen production and water treatment, linking theoretical aspects of bubble dynamics to practical outcomes.

In summary, the exploration of ultrasound-induced cavitation presents an understanding of the mechanisms, operational conditions, and applications pivotal to optimizing sonohydrogen production and other sonochemical processes. From the intricacies of cavitation bubble formation, governed by stages like nucleation, growth, stability, collapse, and post-collapse phenomena, to the critical operational parameters such as ultrasound frequency, intensity, and sonication time, each element plays a vital role in influencing the efficiency and outcome of ultrasound-assisted experiments. The selection of sono-reactor designs and understanding of bubble dynamics are essential for maximizing the potential of cavitation-based applications. Furthermore, the detection methods for cavitation bubbles, ranging from active and passive to self-sensing techniques, offer valuable insights for monitoring and controlling the cavitation process. This body of knowledge not only enhances our grasp of the fundamental science behind cavitation but also paves the way for innovative applications in energy production, environmental protection, and beyond. The synergy between advanced water treatment methods and cavitation technology underscores a holistic approach to addressing global challenges related to energy, water scarcity, and environmental sustainability.

4. Experimental setups and applications using ultrasonic methods

This section begins with an overview of various experimental setups and applications using ultrasounds. Then particularly the experimental setups in water treatment and hydrogen production will be reviewed. As discussed earlier, ultrasonic technology is increasingly utilized in a variety of sectors for diverse applications. In the medical treatment field, it is employed in therapeutic ultrasound, ultrasonic surgical instruments, and lithotripsy. In the realm of quality control and precise instrumentation, ultrasonic technology is pivotal for non-destructive testing thickness gauging and ultrasonic flow meters. In medical imaging, ultrasound technology is indispensable for creating real-time images of organs, tissues, and blood flow. Industrial applications of ultrasound are also wide-ranging, including ultrasonic welding, ultrasonic cutting, and industrial cleaning. Ultrasonic cleaners leverage cavitation bubbles to remove contaminants from delicate items or intricate parts. The following are some example studies that employed different types of sono-reactor configurations as illustrated in Fig. 5.

Using Type B, Polachini et al. [31] investigated the efficiency of electric-acoustic energy conversion in acid suspensions. The experiments were conducted with 2 L of untreated CB acid suspensions, which were placed in a jacketed stainless-steel chamber. The suspensions were at a constant temperature of 20 °C using a thermostatic bath. Ultrasound was applied to the suspensions using an ultrasonic processor coupled with a 22 mm diameter titanium sonotrode. The frequency of the system was set at 24 kHz. Different input powers ranging from 160 to 400 W were used in the experiments and acoustic intensity ranged from 12.90

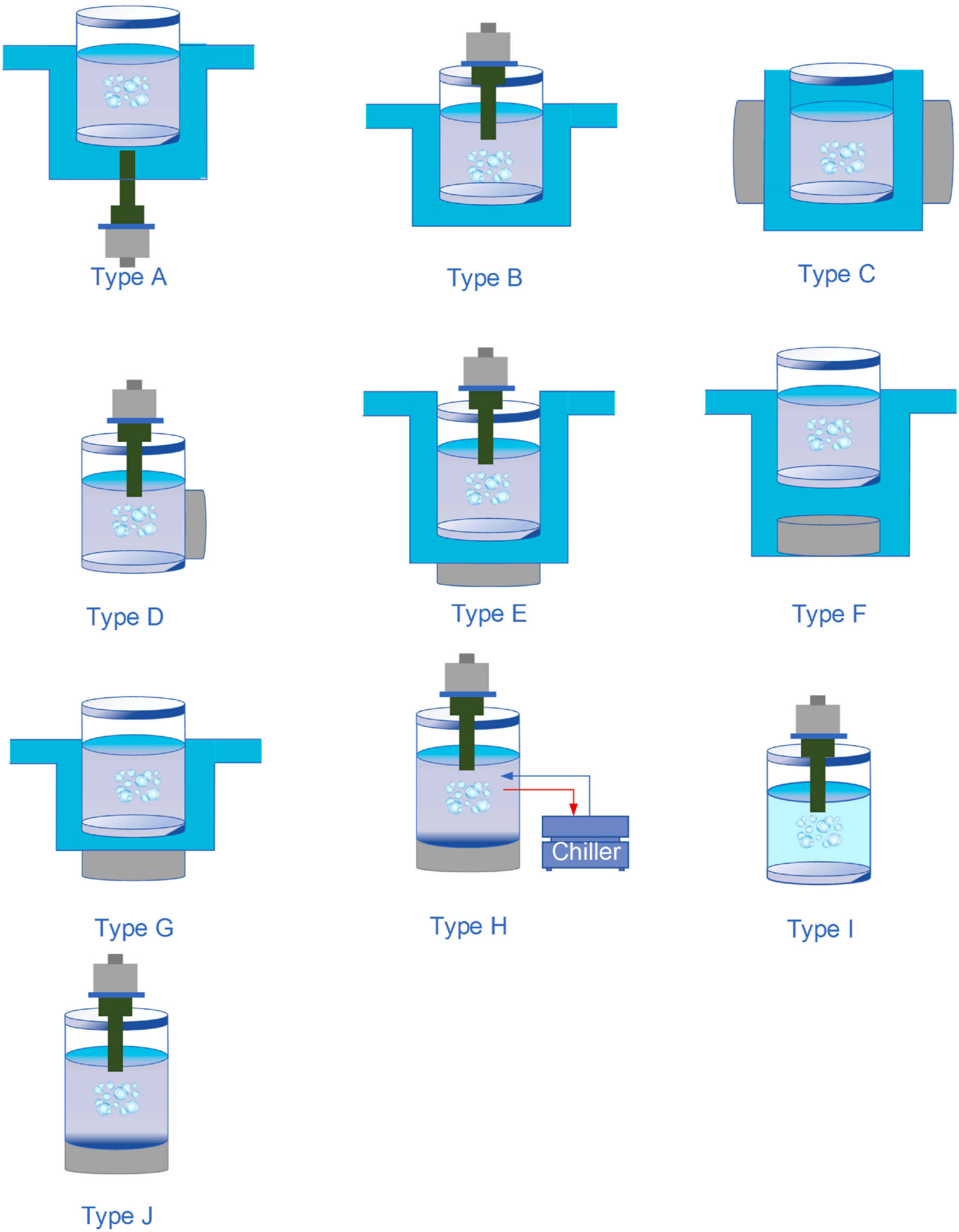

Fig. 5. Various sono-reactor configurations for acoustic cavitation bubble generation.

Table 2
Comparative analysis of the twelve sono-reactor configurations for acoustic cavitation bubble generation.

Type	Probe Location	Plate Location	Cooling Method	Advantage	Disadvantage
A	Bottom-Bath	No Plate	Natural	• Lower construction costs due to a natural cooling method. • Bottom placement of probe may facilitate bubble dispersion.	Not suitable for configurations requiring top placement of probe.
B	Top-Vessel	No Plate	Natural	• Lower construction costs due to a natural cooling method. • Probe at top may facilitate maintenance.	Possible inefficient dispersion of bubbles.
C	No Probe	Right and left side -Not directly connected to the vessel	Natural	• Lower construction costs due to a natural cooling method. • Both probe and plate utilized for better efficiency.	Complexity in setup.
D	Top-Vessel	Right- Direct connection to the vessel	No cooling	• The right placement of plate may offer unique benefits. This might be useful in some experiments. • Probe at top may facilitate maintenance. • Both probe and plate utilized for better efficiency.	Lack of cooling method
E	Top-Vessel	Bottom- Not directly connected to the vessel	Natural	• Lower construction costs due to a natural cooling method. • Probe at top may facilitate maintenance. • Both probe and plate utilized for better efficiency.	No direct connection of plate to vessel can lead to inefficiency.
F	No Probe	Bottom- Not directly connected to the vessel	Natural	• Lower construction costs due to a natural cooling method.	Lack of probe may affect efficiency.
G	No Probe	Bottom- Not directly connected to the vessel	Natural	• Lower construction costs due to a natural cooling method.	Lack of probe may affect efficiency.
H	Top-Vessel	Bottom- Direct connection to the vessel	Forced	• Chiller offers effective cooling. Both probe and plate utilized. • Probe at top may facilitate maintenance. • Both probe and plate utilized for better efficiency.	Complexity and cost of setup.
I	Top-Vessel	No Plate	No cooling	• Probe at top may facilitate maintenance.	Lack of cooling method could affect efficiency.
J	Top-Vessel	Bottom- Direct connection to the vessel	No cooling	• Probe at top may facilitate maintenance. • Both probe and plate utilized for better efficiency.	Lack of cooling method could affect efficiency.

to 68.57 W/cm^2.

Using Type D, Son et al. [32] utilized a large-scale sonoreactor with potassium iodide dosimetry to investigate the correlation between the distribution of cavitation energy at different ultrasonic frequencies and sonochemical efficiency. The frequencies analyzed were 35, 72, 110, and 170 kHz, and the power delivered to the system was 240 W. According to the study, the most significant and consistent dispersal of cavitation energy was discovered at 72 kHz, and the distance covering half of the cavitation energy was greater at 35 kHz compared to 72 kHz. This implies that the cavitation energy for a single cycle was higher at a lower frequency. However, the cavitation energy distribution for 110 and 170 kHz ultrasound was very low and poor. The relationship between cavitation energy and sonochemical efficiency was best fitted quadratically, and the sonochemical effectiveness was assessed across a spectrum of cavitation energy ranging from 31.76 to 103.67 W. During this investigation, the water temperature inside the sonoreactor was preserved between 18 and 19 °C without employing any cooling mechanism, and the examination was performed after aerating the water with three air diffusers for 20 min to decrease the impact of degassing on the water.

Using Type G, Dehane et al. [33] conducted a study to calculate the number of bubbles in the sonicated liquid. Sonolysis experiments were evaluated at an ultrasound frequency of 300 kHz using a standing wave sonoreactor with a capacity of 500 mL. The piezoelectric disk was powered by an electric generator, enabling it to operate at different electric powers of 20, 40, and 60 W. Water was used as the sonicated liquid in all experiments.

Using Type J, Son et al. [34], utilized a 20 kHz-probe system to examine the cavitation activity under different experimental circumstances. The study investigated the effect of various factors on sonochemical reactions in a probe type sonicator system, and suggested optimal conditions, including probe placement close to the bottom and an optimal liquid height, for inducing high sonochemical activity. In their study, they used a 20-kHz probe type sonicator with a threaded end type probe and a replaceable tip made of titanium alloy, which had a diameter of 13 mm. The probe was placed in a glass vessel with a volume of 500 mL.

In addition to the applications mentioned above, ultrasounds can also be integrated into energy systems for water treatment and hydrogen production, similar to the studies [35,36]. These applications demonstrate the versatility of ultrasound technology in various fields of mechanical engineering, particularly in sustainable energy and environmental solutions.

4.1. Experimental setups and applications utilizing ultrasound for hydrogen production

There are a few techniques to produce hydrogen using ultrasounds. A technique to spilt water molecules into oxygen and hydrogen gases is water electrolysis using an electric current. This is useful in industrial and scientific applications, such as hydrogen fuel production and the establishment of clean energy storage systems. Use of ultrasound technology can increase the efficiency of water electrolysis using improving the rate of reaction and reducing the energy input required to produce hydrogen and oxygen gases. Applying ultrasound waves to water during the electrolysis process, can facilitate the formation of gas bubbles, which increases the surface area of the electrodes and helps more efficient gas separation [37]. Additionally, the mechanical agitation caused by the ultrasound waves can also promote the movement of ions and electrons, further enhancing the efficiency of the process.

In this section different experimental set-ups are demonstrated for those including hydrogen or hydrogen peroxide production.

Petrier and Francony [38] and Jiang et al. [39] performed studies using ultrasonic waves at a frequency of 20 kHz, generated by a titanium horn with a 3.5 cm diameter, powered by a Branson Sonifier 450. They also used higher frequency transducers operating at 200, 500, and 800 kHz, with a piezoelectric disc of 4 cm diameter, connected to a high-frequency power source from Electronic Service. On the other

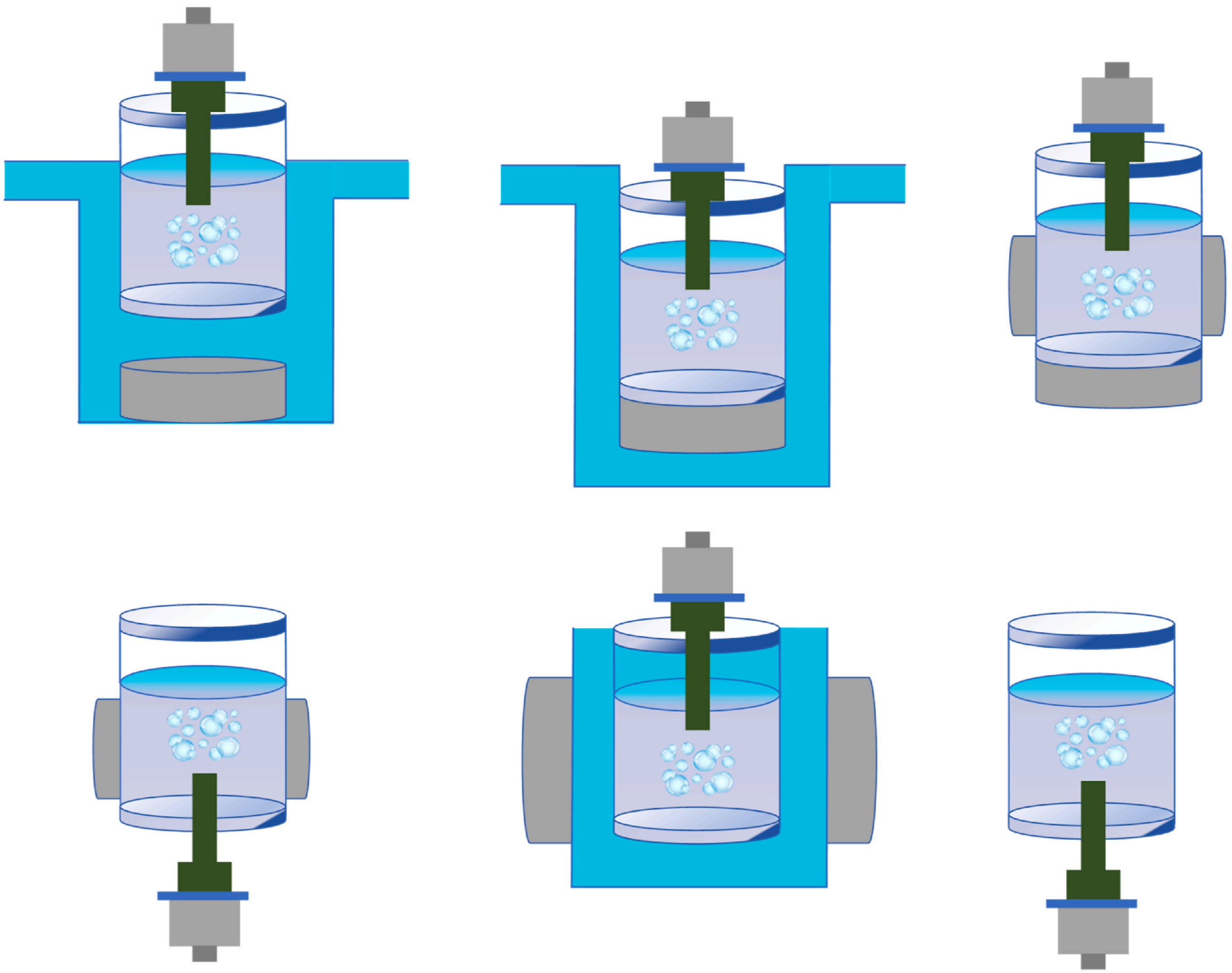

Fig. 6. Some potential sono-reactor configurations proposed for future studies.

hand, Merouani et al. [40] carried out experiments using a 300 kHz piezoelectric disc, from which ultrasonic waves were emitted from the bottom. Additionally, they conducted tests at even higher frequencies of 585, 860, and 1140 kHz, employing a Meinhardt multi-frequency transducer (model E/805/T/M) with a 5.3 cm diameter. The experiments demonstrated an increase in the production rate of H2O2 with the frequency increase, reaching a peak before declining. This trend is thought to be due to the formation of bubble clouds that dampen the acoustic intensity, consequently decreasing the H2O2 production rate.

Using Type A, the influence of ultrasound on the behavior of bubbles on a stainless steel plate electrode during HER was explored in the study of Cho et al. [41]. In this experiment, a reactor with dimensions of 50 × 50 × 65 mm and a working volume of 20 mL was used. Ultrasound was generated by installing a 700 W single probe type ultrasonic transducer operating at 20 kHz. A sonotrode with a diameter of 10 mm was used, which was submerged 20 mm through the base of the reactor with the aid of an O-ring. The ultrasonic probe tip was positioned 10 mm away from the base of the inner cell. An electrolyte consisting of distilled water and NaOH was used in the experiment. The velocity and diameter of bubbles in HER were observed in the analysis, with data collected through high-speed imaging under both sonication and silent conditions.

In the study of Lee and Oh [42], the aims were to assess the increase and decrease in the production of H_2O_2 and to observe the regions where the reaction caused by sound waves occurs. The experiments were conducted employing Type C and using frequencies of 28, 584, and 970 kHz. For the 28 kHz frequency, there were six bolt-clamped langevin transducer (BLT) units with a diameter of 45 mm. For the 584 kHz and 970 kHz frequencies, there were two piezoelectric transducer (PZT) units each. The temperature of the liquid inside the reactor was maintained at 20 ± 1 °C. Various power levels were employed, including 100, 150, 200, 300, and 400 W. The ultrasonic reactor operated in this study was constructed from stainless steel. It had a total size of approximately 4 L. A solution volume of 3.9 L was utilized, and samples of 3 mL were gathered for H_2O_2 investigation every 10 min for a total of 60 min.

Ji et al. [43], using Type E, conducted a study comparing acoustic cavitation at various ultrasonic frequencies: 20, 100 and 362 kHz. Experimental investigations were performed to examine the chemical activity, specifically the yield of H_2O_2, produced by cavitation bubbles at these frequencies. The results revealed that at 100 kHz, the cavitation bubbles exhibited a transitional behavior between the high and low frequency ranges. During the sonolysis experiments, a volume of 250 mL of distilled water was utilized. The temperature of the solution was carefully maintained at a constant level of 18 ± 2 °C.

Mizukoshi et al. [44], using Type F, conducted a study in which they subjected organic liquids to sonication at different temperatures under an argon atmosphere. In their study one of the main decomposition products was hydrogen. The sonication process was evaluated using an

Table 3
Comparison of acoustic cavitation bubbles and Taylor bubbles.

Aspect	Taylor Bubbles	Acoustic Cavitation Bubbles
Formation	Form in two-phase flow systems, especially in narrow vertical tubes.	Form in a liquid due to rapid pressure changes induced by sound waves.
Shape	Elongated, bullet-like shape with a distinct nose and a trailing liquid film.	Generally spherical or near spherical.
Size	Large, often occupying a significant portion of the tube's cross-section.	Smaller in size, not constrained by tube dimensions.
Flow Regime	Occur in slug flow regimes within tubes.	Not specific to any flow regime in tubes; occur in bulk liquid.
Influencing Factors	Influenced by tube diameter, fluid viscosity, surface tension, and gravity.	Influenced by the frequency and amplitude of sound waves, fluid properties, and ambient conditions.
Behavior	Stable elongated shape, moving steadily along the tube.	Dynamic behavior with cycles of growth and collapse, influenced by oscillatory pressure fields of sound waves.
Typical Environment	Found in low-viscosity liquids in vertical tubes.	Can occur in various liquids subjected to ultrasonic or acoustic energy.
Gravitational Influence	Gravitational forces play a significant role in determining their shape and motion.	Gravitational forces are less influential compared to the forces induced by sound waves.

ultrasonic generator with a frequency of 200 kHz and a power density of 6 W/cm. An oscillator made of barium titanate with a diameter of 65 mm was used. The sonication experiments were carried out in a cylindrical glass vessel with an inside diameter of 20 mm and a total volume of 38 mL. A volume of 10 mL of argon-purged organic liquids was sonicated. The sonolysis experiments were conducted at various temperatures ranging from 5 to 50 °C, and a water bath was used to control the vapor pressure of the organic liquids. The resulting gaseous sonolysis products included carbon monoxide, propylene, ethylene, acetylene, propane, ethane, methane, and hydrogen.

In their study, Mohapatra et al. [45], presented the utilization of sonoelectrochemistry to create nanotubes, which are then examined for their ability to produce hydrogen through photoelectrocatalysis via water splitting (Type F with electrodes). The process involved anodization of titanium foils in a 300 mL electrolytic solution, with the assistance of ultrasonic waves operating at a power of 100 W and a frequency of 42 kHz. The experiments were conducted at the room temperature ranging from 22 to 25 °C.

Zadeh [46], discussed the use of alkaline water electrolysis coupled with ultrasound to produce clean hydrogen. The study employed Type F with electrodes and delved into the influence of ultrasound on a typical water electrolysis cell and other significant variables, such as the active surface area of electrodes and the electrolyte solution. The hydrogen yield was quantified with a hydrogen flowmeter, and the mean productivity efficiency of the electrolysis cell was calculated to be 78%. The findings revealed that the implementation of ultrasound raised the production efficiency by 4.5% and enhanced energy efficiency by 1.3%. Additionally, an increase of 43.75% in the electrode active surface area improved current generation by about 70%, and the hydrogen generation was enhanced by about 50%. Additionally, the examination determined that the utilization of ultrasound led to the elimination of bubbles from the electrode and electrolyte solution surfaces, thereby preparing the electrode surface for electrochemical reactions, which in turn improved the production of hydrogen.

In the study of Pham et al. [47], an approach has been developed to explore the potential of using ultrasound power for converting waste into energy in an environmentally friendly manner. The sonolysis process was carried out in an ultrasonic cleaner bath operating at 40 kHz to produce CO, CH_4 and hydrogen (using Type G). The experiment involved using a 10 mL solution of Rhodamine B (RhB) with a known concentration, ranging from 5 to 100 ppm, which was placed in a 20-mL headspace vial with a septum cap. In addition, the acoustic intensity was found to be approximately 38 W/L. The overall experimental arrangement for this study, consisted of an Ultrasonic bath, a Reactor vial, an Inside thermocouple, an outside thermocouple, a timer controller, two peristaltic pumps, a cooling coil, a cooling bath thermocouple, and an interface.

In the study of Shestakova et al. [48], the sonoelectrochemical decomposition of FA (formic acid) was investigated with the objective of optimizing the electrochemical and sonochemical parameters involved in FA degradation (using Type G with electrode). While the primary focus of the study was on the degradation and mineralization of FA, hydrogen generation was a byproduct of the electrolysis process involved in the sonoelectrochemical decomposition. According to the study, the most substantial mineralization of FA (97%) was attained by utilizing 1176 kHz ultrasonic irradiation, in conjunction with 20 mA electrolysis, for 120 min. Moreover, the investigation discovered that the fastest degradation kinetics of FA, with a constant rate of 0.0374 min^{-1}, occurred at 381 kHz, 20 mA, and an ultrasonic power of 0.02 W/cm^3.

The study of Kerboua and Merabet [49], aimed to explain the formation mechanism of acoustic cavitation in alkaline sono-electrolysis, specifically focusing on factors such as hydrogen production rate and the contribution of ultrasounds the overall process. In this experiment Type G with electrodes was employed. In an H-cell, a 300 mL solution of KOH was subjected to electrolysis while being exposed to ultrasonic waves in a bath. The electrolyzer was powered by a DC power supply providing direct current. The ultrasonic bath operated at a frequency of 40 kHz and served as a continuous source of indirect sonication. The sonicator utilized in this process had an input electric power rating of 60 W.

Singh and Sinha [50] conducted a study on the photocatalysis of water using visible light, with ultrasound to evaluate the hydrogen production. In their study they used Type I. They utilized a stainless-steel tip with a diameter of 4 mm, linked to a PZT transducer type ultrasound generator able to produce ultrasound at a frequency of 20 kHz and varying input powers from 10 to 40 W. The catalyst used was cadmium sulfide (CdS) supported by reduced graphene oxide (RGO), with 1 g of catalyst suspended in 250 mL of aqueous solution. The pH of the solution was maintained at 8.6, and the pressure inside the reactor was kept close to atmospheric pressure. The temperature of the liquid was found to be approximately 299 K.

McMurray et al. [51], using Type I and electrodes evaluated the use of a titanium sonotrode and ultrasonic irradiation to enhance the rate of electrochemical hydrogen evolution in a neutral aqueous electrolyte. They utilized a sono-electrochemical cell arrangement with a titanium (Ti) tip sonotrode. For the experiment, they employed a 20 kHz ultrasound generator equipped using a typical 10 mm flat Ti tip. The power level was adjusted to 26 W cm^2. The electrolyte temperature was maintained within 1 °C during the experiment and voltametric assessments were kept at 30 °C.

In synthesizing the diverse experimental approaches outlined, it becomes evident that the application of ultrasound technology in hydrogen and hydrogen peroxide production presents a multifaceted area of research with varying methodologies, outcomes, and efficiencies. A comparative analysis reveals that the frequency of ultrasound waves plays a critical role in optimizing the production rates, with studies demonstrating that higher frequencies tend to increase H_2O_2 production up to a certain peak before a subsequent decline, attributed to the formation of bubble clouds that dampen acoustic intensity. Similarly, the choice of materials for electrodes and transducers, such as titanium and piezoelectric discs, alongside the design of the electrolytic cell, significantly influences the efficiency of gas production by affecting bubble formation and the movement of ions and electrons. The experimental setups, varying from single probe ultrasonic transducers to multi-

frequency systems, highlight the importance of mechanical agitation and the surface area of electrodes in enhancing electrolysis and sonolysis reactions. Furthermore, the incorporation of temperature control and chemical additives is shown to have a notable impact on reaction kinetics, pointing towards an intricate balance between physical and chemical parameters in optimizing hydrogen production. This synthesis not only underscores the complexity of factors influencing ultrasound-assisted electrolysis but also opens avenues for future research aimed at refining these parameters to achieve higher efficiencies and scalability in hydrogen fuel production technologies.

4.2. Applications utilizing treated water for hydrogen production

Water, a vital resource for all life on Earth, has become increasingly important as the global population expands and industrial activities intensify. This surge in demand has necessitated the development of effective water treatment methods to ensure a sustainable supply of clean water. Water treatment processes remove contaminants and undesirable components, making it safe for consumption and various industrial applications. The significance of water treatment becomes even more pronounced when considering innovative applications like the sonohydrogen production process. Utilizing treated water in the sonohydrogen process not only enhances the efficiency of hydrogen production but also ensures that the process is environmentally sustainable. The quality of water used in the sonohydrogen process is crucial, as impurities can affect the reaction dynamics and the overall energy efficiency of the system.

4.2.1. Water treatment

The availability of fresh, potable water is becoming threatened due to pollution and overexploitation of natural water sources. To address these challenges and ensure a sustainable future, innovative water treatment techniques are developed to purify wastewater, making it safe for reuse or discharge into the environment.

In Table 4 some of the most effective methods used to remove contaminants from wastewater are explored using ultrasound techniques. While there is extensive research on water treatment methods, there is a notable scarcity of studies focusing on the production of hydrogen using treated water.

4.2.2. Hydrogen production with treated water

In the context of sonohydrogen production, treated water serves as the primary reactant. The process involves the dissociation of water molecules into hydrogen and other radicals, a reaction that is energy-intensive but holds significant potential for clean energy generation. By employing ultrasonic irradiation, the sonohydrogen process can efficiently produce hydrogen, a clean and renewable energy source.

The integration of water treatment and sonohydrogen production exemplifies a holistic approach to resource management and energy generation. By utilizing treated water, the sonohydrogen process not only contributes to resolving the energy crisis but also supports water conservation efforts, showcasing an innovative synergy between environmental sustainability and energy production. This approach ensures that the increasing demands for clean water and sustainable energy are addressed in a manner that benefits both the environment and future generations.

Fig. 7 presents the current authors' proposed method for producing hydrogen sonically using treated water. The process begins with the treatment of fresh water to remove impurities and contaminants. This is typically done through several stages, including coagulation, sedimentation, filtration, and disinfection.

- Coagulation involves adding chemicals to the water that bind with dirt and dissolved particles, forming larger particles called flocs.
- Sedimentation allows the flocs to settle to the bottom of the water supply due to gravity.
- Filtration passes the water through filters to remove smaller particles.
- Disinfection uses chemicals or physical processes to kill any microorganisms present.

After the water is treated, it is fed into a reactor vessel where it undergoes a process to produce hydrogen. The sono part of sonohydrogen suggests the use of sonication or ultrasound technology. Sonication involves the application of sound waves to agitate particles in a sample, and in the context of hydrogen production, it can be used to induce the breakdown of water molecules into hydrogen and oxygen gas through a process called sonolysis.

The sonolysis of water involves the formation of microbubbles due to ultrasound, which then collapse and create localized high temperatures and pressures, leading to the dissociation of water molecules. The hydrogen produced in the reactor vessel is then captured and stored. Hydrogen storage can be in the form of high-pressure tanks, as a liquid in cryogenic tanks, or through metal hydrides or other chemical means. Stored hydrogen is a versatile energy carrier that can be used for various

Table 4
Some potential water treatment methods using ultrasound techniques.

Water Treatment Method	Description	Source
Suspended Solid Removal	Separates and removes solid particles like dirt and debris through sedimentation or filtration, improving water clarity and reducing environmental harm.	[52]
Adsorption Techniques	Involves contaminants binding to the surface of a solid adsorbent, effectively removing organic pollutants, heavy metals, and certain chemicals.	[53]
Ion Exchange	Exchanges ions in wastewater with a solid resin, removing dissolved inorganic pollutants like heavy metals, calcium, and magnesium ions.	[54]
Reverse Osmosis	Utilizes a semi-permeable membrane and applied pressure to purify water, leaving behind pollutants.	[55]
Electrodialysis	Uses an electric field to remove ions, particularly useful in desalination processes.	[56]
Chemical Oxidation	Employs powerful oxidizing agents to break down organic pollutants into simpler, less toxic substances.	[57]
Nutrient Removal	Targets the reduction of nutrients like nitrogen and phosphorus to prevent eutrophication in water bodies.	[58]
Solar Desalination	Leverages solar energy to produce fresh water by evaporating and condensing water, leaving behind salts and impurities.	[59]
Advanced Oxidation Processes (AOPs)	Utilizes powerful oxidants to generate hydroxyl radicals that degrade a wide range of pollutants.	[60]
Ultrasonic Disinfection	Kills microorganisms using cavitation bubbles created by high-frequency sound waves.	[61]
Ultrasonic Degradation of Organic Compounds	Facilitates the removal of organic pollutants in water through sonochemical degradation.	[62]
Ultrasonic Membrane Cleaning	Cleans membranes in water treatment processes, dislodging materials like biofilms and particles.	[63]
Ultrasonic AOPs	Combines ultrasonic waves with other advanced oxidation techniques for water treatment, generating reactive species like hydroxyl radicals.	[64]
Ultrasonic Dechlorination	Removes chlorine or chloramine from water using high-frequency sound waves.	[65]
Ultrasonic Treatment for Algae-Laden Water	Optimizes algal removal and the release of algae organic matter in water treatment.	[66]
Ultrasonic Treatment of Textile Wastewater	Employs high-frequency ultrasound for the degradation of Indigo dye substances in textile wastewater.	[67]

applications, including fuel cells for electricity generation, hydrogen-powered vehicles, and as a feedstock for chemical industries.

This process allows for the production of clean hydrogen fuel from water without the carbon emissions associated with traditional hydrogen production methods like steam reforming of natural gas. It's an example of using alternative energy technologies to promote sustainability and reduce reliance on fossil fuels.

In a study, Rashwan et al. [68], detailed the significant volumes of sewage in Canada and discussed various wastewater treatment methods, such as coagulation and flocculation. It highlights the integration of ultrasonic techniques to enhance these processes. Central to the paper was the discussion on electrocoagulation-enhanced technology for removing pollutants from water and the detailed explanation of the ultrasonic-aided flocculation process, which improves particle disintegration and flock formation in wastewater treatment. They proposed an integrated system for treating textile wastewater, which included steps like sedimentation, filtration, and reverse osmosis, followed by a sonoreactor for hydrogen production. The study concluded that ultrasonic wastewater treatment could offer substantial benefits, including the reduction of disposal mass and the production of useful gases like hydrogen, while achieving high removal efficiencies and reducing energy consumption.

In summary, the integration of advanced water treatment methods with sonohydrogen production represents a forward-thinking approach to simultaneously addressing the challenges of water scarcity, environmental sustainability, and the search for renewable energy sources. Water treatment technologies play a critical role in purifying water for use in sonohydrogen production, ensuring that the process is efficient, environmentally friendly, and capable of producing high-purity hydrogen. This synergy between water treatment and hydrogen production underscores the importance of innovative solutions in overcoming contemporary environmental and energy challenges. By harnessing treated water for hydrogen production, one can leverage the vast potential of sonohydrogen technology to contribute significantly to sustainable energy landscapes. This approach not only helps in conserving one of our most precious resources, water, but also in advancing the use of clean, renewable energy sources for a more sustainable future.

5. Comparative analysis of experimental setups for hydrogen production

In this section, various parameters affecting the hydrogen production rate are firstly discussed comparatively, and then different experimental setups are evaluated accordingly.

5.1. Key parameters for comparison

When it comes to constructing an experimental setup for sonohydrogen production, there are various parameters to consider (see Fig. 8). The efficiency of the sonohydrogen production process can be affected by several factors, such as power density, ultrasound frequency and reactor size [69].

5.1.1. Frequency

The acoustic frequency is a key parameter in sonohydrogen production. High-frequency ultrasound waves can generate high-pressure regions in the solution, which are essential for the formation and subsequent collapse of cavitation bubbles. This collapse produces conditions conducive to the dissociation of water molecules into hydrogen and oxygen. The effectiveness of ultrasound in promoting hydrogen production depends on the cavitation phenomenon. Lower frequencies are more effective for creating cavitation bubbles, which is essential for disrupting water molecules. The results of a parametric analysis of a study [30] indicated that the greatest cavitation energy aligns with the peak negative pressure, which occurs within the frequency range of 60–80 kHz.

The pressure variation P(t) in an elastic medium can be described by

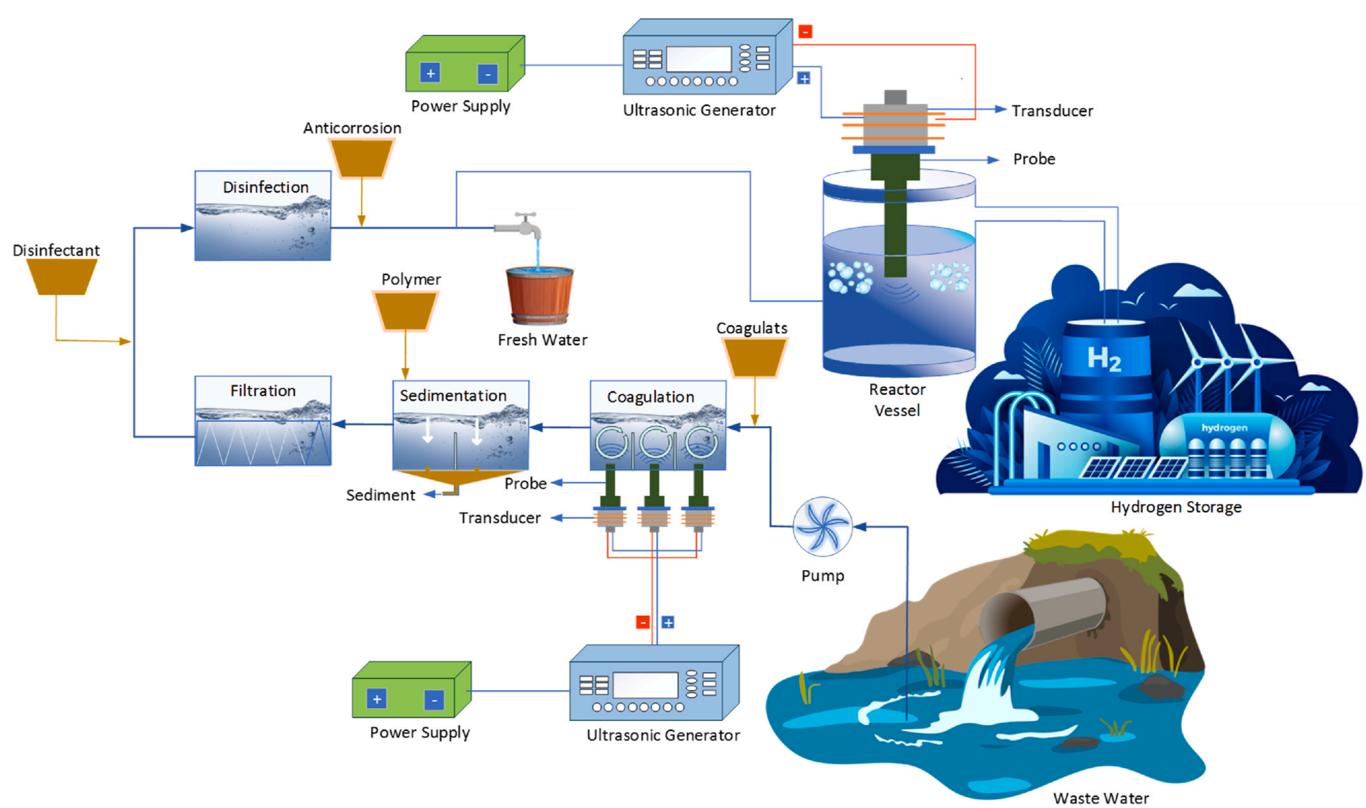

Fig. 7. A potential integrated system designed for sonic hydrogen production with treated water.

the following equation [70]:

$$P(t) = P_A \sin(2\pi ft + \theta) \tag{16}$$

where P_A represents the amplitude of the acoustic pressure, f denotes the wave's frequency.

As the frequency rises, it becomes essential to elevate the amplitude (or intensity) of the irradiation to preserve the same level of cavitation energy. This makes inducing cavitation in liquids at higher frequencies, like those in the MHz range, more challenging. The rationale behind this is those higher frequencies lead to shorter compression and rarefaction cycles. For cavitation to occur, sufficient time is needed for the molecular separation to happen.

5.1.2. Power

Power, or the intensity of the ultrasound waves, also significantly influences the sonolysis process. A higher power level leads to more intense cavitation, resulting in higher pressures and temperatures that facilitate the splitting of water molecules. The power of the ultrasound source should be enough to induce sufficient cavitation. However, excessive power can lead to energy inefficiency and equipment damage. The optimal power depends on specific experimental setup and reactor size.

The intensity of ultrasound power is calculated by dividing the power transmitted to a liquid by the surface area of the ultrasonic transducer. The relationship between ultrasonic power intensity and acoustic pressure can be described by the following formula [70]:

$$I = \frac{P_0^{\,2}}{2\rho C} \tag{17}$$

where I, is the sound wave's power intensity, P_0 is the acoustic pressure, ρ is the liquid's density, and C is the sound speed in the liquid. Higher acoustic pressure results in more frequent and intense cavitational events. The highest reaction rate usually corresponds with the optimal power intensity. However, increasing the power beyond this point can decrease the reaction rate due to the bubble shielding effect.

At high power intensities, numerous cavitation bubbles accumulate around the transducer, which obstructs sound wave propagation because of both scattering and absorption, particularly for bubbles of resonant size. This leads to a decrease in sound wave intensity, which diminishes more quickly with distance from the source at very high-power intensities compared to optimal intensities.

5.1.3. Temperature

Temperature is another important variable affecting sonohydrogen production. Elevated temperatures can provide the energy required to dissociate water molecules into oxygen and hydrogen. However, overly high temperatures can cause the recombination of hydrogen and oxygen, reducing the efficiency of hydrogen production.

The average gas bubble temperature can be determined as [27]:

$$\dot{T} = \frac{4\pi R(t)^2}{C_v}\left(\frac{L(T_0 - T)}{L_{th}} - \dot{R}P_g\right) \tag{18}$$

where C_v is the heat capacity at constant volume, T_0 is the initial gas temperature (293 K). The L_{th} can be calculated as:

$$L_{th} = \min\left(\sqrt{\frac{aR(t)}{|\dot{R}(t)|}}, \frac{R(t)}{\pi}\right) \tag{19}$$

where a is the gas thermal diffusivity and can be calculated as follow:

$$a = \frac{L}{C_p \rho_g} \tag{20}$$

where C_p is specific heat capacity at constant pressure, L is the gas

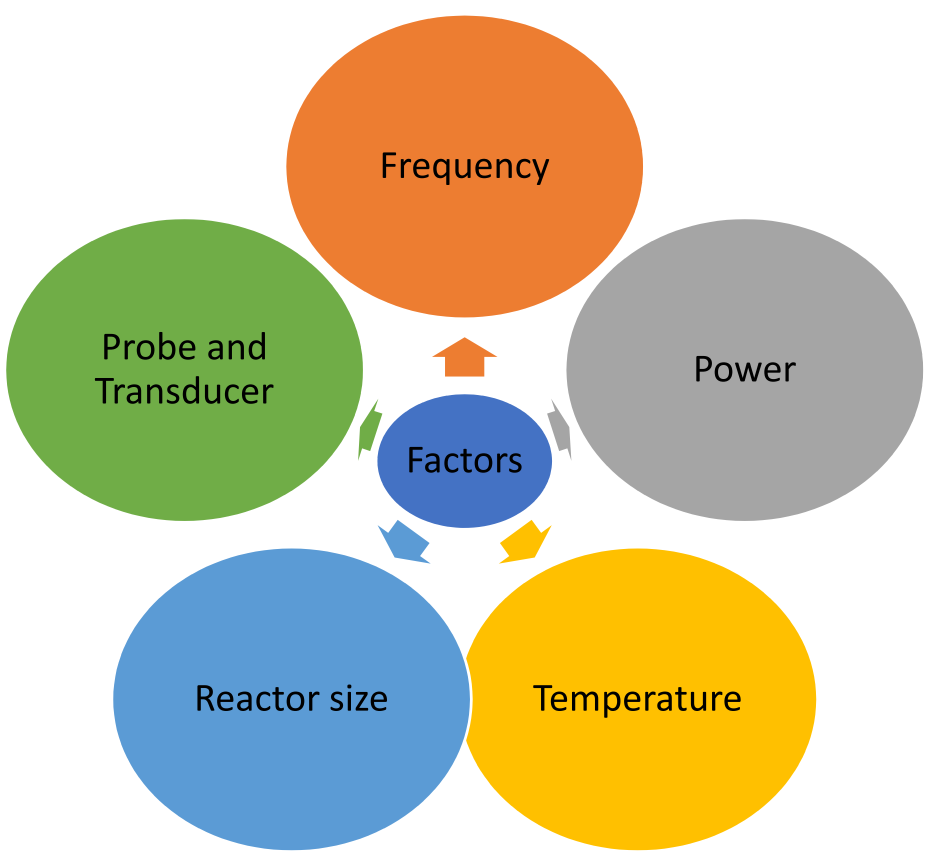

Fig. 8. Key factors affecting sonohydrogen production.

thermal conductivity and ρ_g is the density of gas.

5.1.4. Reactor size

The dimensions and volume of the reaction vessel influence the distribution and stability of cavitation bubbles. This, in turn, affects the overall efficiency of sonohydrogen production. Optimal vessel size should be determined based on the specific objectives and constraints of the experiment. The reactor should be large enough to accommodate the volume of water being treated, but not so large that the ultrasonic waves dissipate ineffectively.

5.1.5. Transducer and probe

The transducer generates ultrasound waves by converting electrical energy into mechanical vibrations, while the probe delivers these waves directly into the liquid medium within the reaction vessel. The type, shape, and material of both the transducer and probe play significant roles in influencing the frequency, power, and directionality of the emitted ultrasound waves. Additionally, the design and positioning of the probe can affect the ultrasound field's distribution and intensity within the vessel. The synergistic performance of the transducer and probe is critical for effective cavitation and, subsequently, efficient sonohydrogen production.

5.2. Effects of some parameters on sonohydrogen production

In this section, the impact of various parameters, including frequency, acoustic intensity, and liquid temperature, on the bubble temperature and the number of moles of H_2 is assessed based on the information provided in Refs. [40,71], and [72].

As shown in Fig. 9, the increase in wave frequency has an expected negative impact on the production of hydrogen molecules and the peak temperature of the bubble. This can be attributed to the decrease in collapse intensity and molar production of acoustic cavitation as the frequency rises.

Essentially, as the wave frequency increases (shortening the acoustic period), less water vapor enters the acoustic cavitation during the expansion phase, leading to a less severe collapse. As a result, the final temperature of the bubble is lower, resulting in a reduced amount of hydrogen molecules generated through water vapor dissociation.

Fig. 10 depicts the relationship between acoustic intensity and the molar yield of hydrogen production, as well as the bubble temperature, at a frequency of 355 kHz. The frequency of 355 kHz is chosen because the micro-bubble exhibits its highest sono-activity around this frequency [72]. It is shown that by increasing acoustic intensity, both bubble temperature and number of moles of H_2 increase. The molar production of hydrogen and the decomposition of methanol are graphically represented across a range of liquid temperatures, specifically at an acoustic intensity of 1 W/cm^2 and a frequency of 355 kHz.

Fig. 11 illustrates the effect of liquid temperature on the bubble temperature and number of moles of H_2. Generally, by an increase in liquid temperature from 293 to 333 K, the number of bubble temperature decreases while the number of moles of H_2 increase.

5.3. Performance evaluation of different experimental setups

In this section the different experimental setups are compared (see Table 5). These are the experimental setups already mentioned in this article.

To guide the optimization of hydrogen and hydrogen peroxide production, a detailed analysis of experimental setups offers valuable insights into the critical factors influencing efficiency and output. These factors include frequency selection, temperature control, the interplay between power and reactor size, as well as the strategic choice of probes and electrodes, and the innovative integration of sonication with traditional electrolysis processes. Each element plays a pivotal role in determining the success and efficiency of the production process, underlining the importance of meticulous setup configuration to achieve optimal results, as discussed below:

1) Frequency selection: The data indicate that the production rate of hydrogen peroxide increases significantly with frequency, up to a certain point. For instance, Petrier and Francony [38] and Jiang et al. [39] show a notable increase in production rates at 200 kHz compared to 20 kHz. This suggests that selecting a higher frequency, within the 200–800 kHz range, could enhance production efficiency, with an optimal frequency likely dependent on other experimental conditions such as liquid temperature and reactor design.

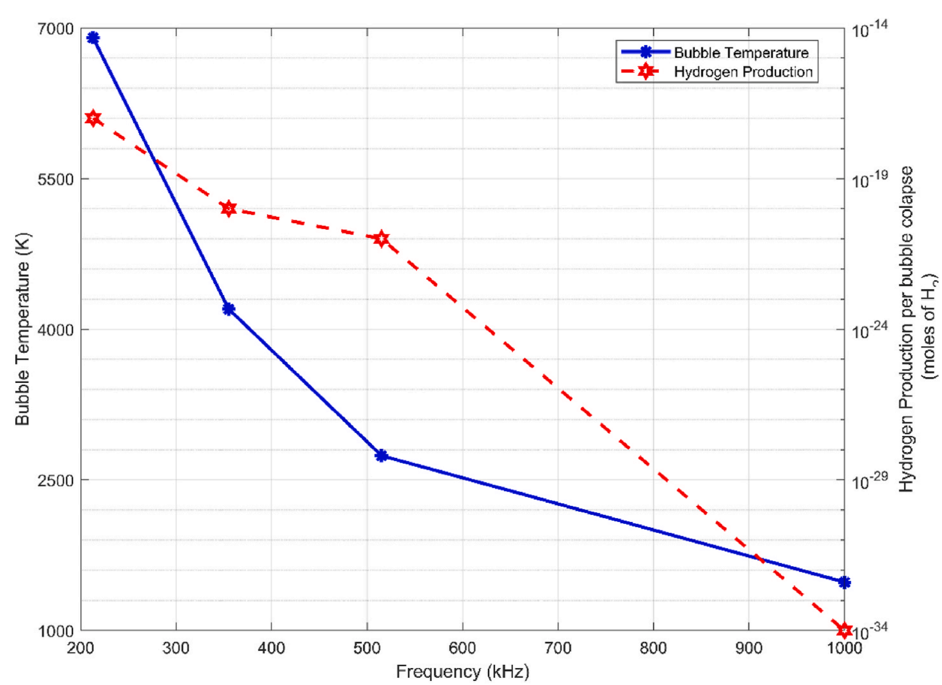

Fig. 9. Effect of ultrasound frequency on the bubble temperature and hydrogen production per collapse (data from Ref. [72]).

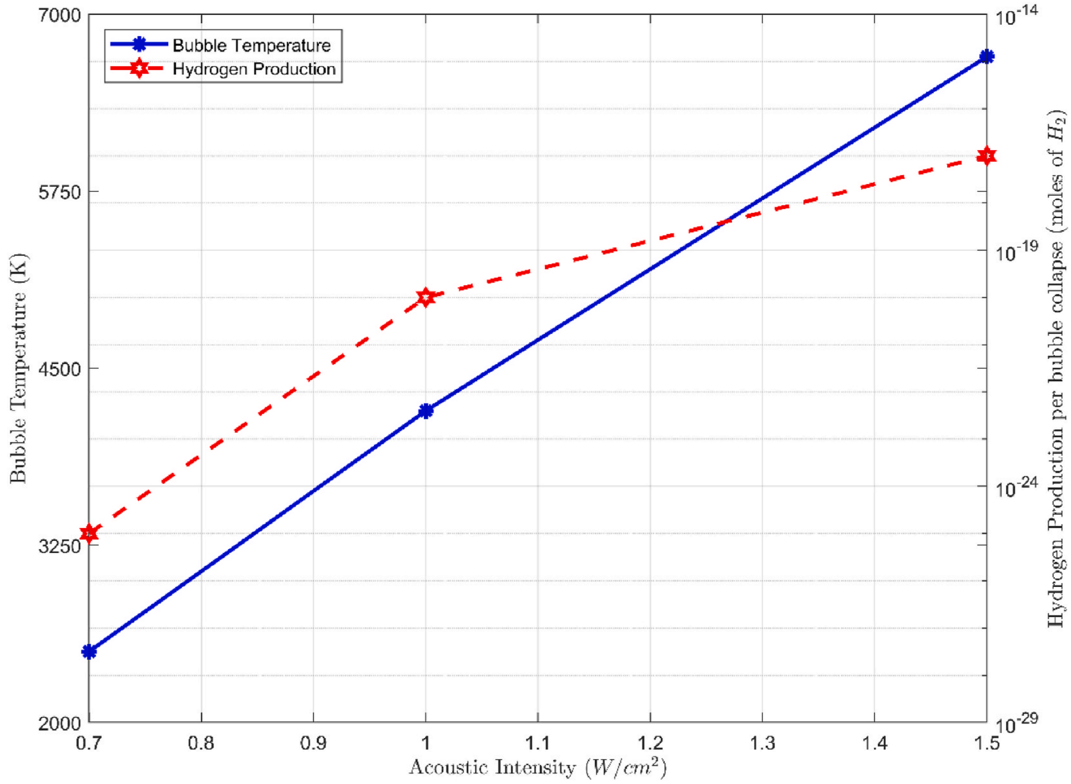

Fig. 10. Effect of acoustic intensity on the bubble temperature and hydrogen production per collapse (data from Ref. [72]).

2) Temperature considerations: Temperature variation, as shown by Jiang et al. [39] and Mizukoshi et al. [44], affects the production rates. A controlled temperature environment, particularly around 20 °C–40 °C, seems beneficial for stabilizing reaction conditions and possibly enhancing production rates. Thus, experiments should aim for temperature control within this range to optimize results.
3) Power and reactor size: Table 5 highlights the relevance of electric power and acoustic intensity in determining the efficiency of

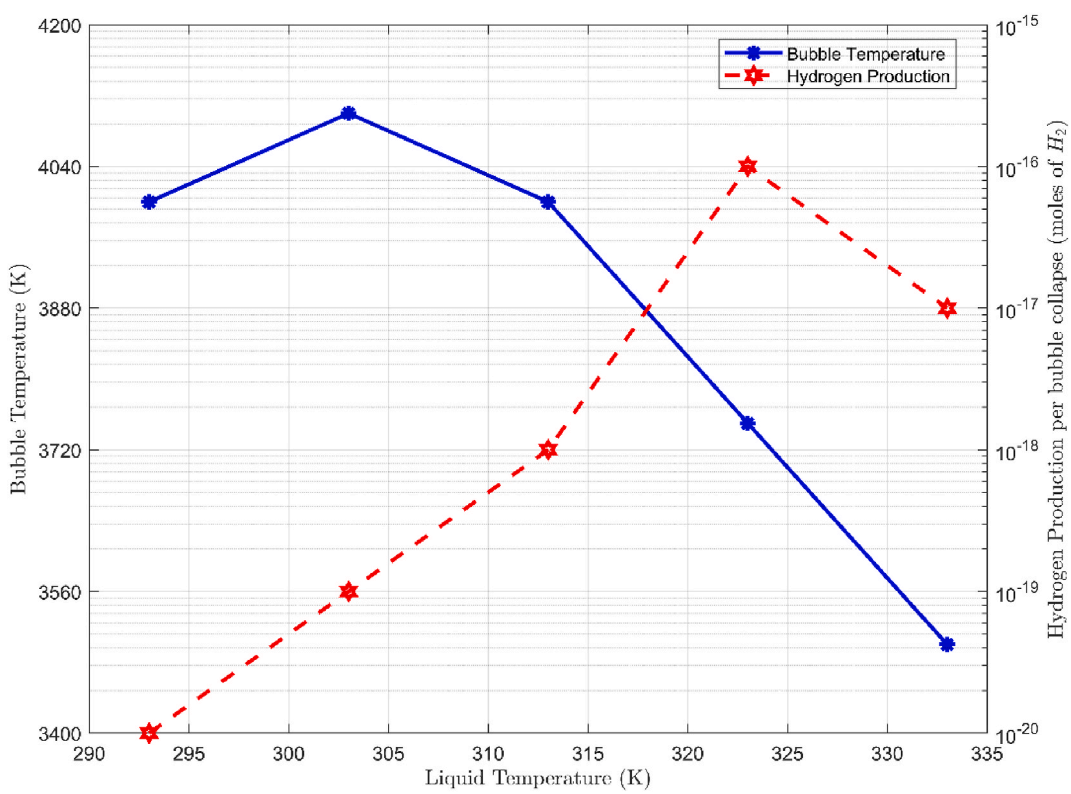

Fig. 11. Effect of liquid temperature on the bubble temperature and hydrogen production per collapse (data from Ref. [72]).

experimental setups for hydrogen or hydrogen peroxide production. Optimizing power levels in accordance with the specific dimensions of the reactor can lead to enhanced efficiency. This optimization involves a careful consideration of how acoustic intensity interacts with the reactor's volume to maximize the efficacy of the sonication process. Zadeh's study [46], for instance, demonstrates that focusing on energy efficiency within these parameters can lead to notable enhancements in production efficiency, suggesting that the strategic adjustment of power relative to reactor size is crucial for improving the outcomes of such experiments.

4) Probe and electrode selection: The choice of probes and electrodes, such as the titanium sonotrode used by McMurray et al. [51] and the barium titanate oscillator by Mizukoshi et al. [44], can significantly impact the efficiency of the process. Selection should be based on the material's ability to withstand prolonged ultrasonic exposure and its effectiveness in facilitating the desired chemical reactions. The setup involving two electrodes for anodization, as described by Mohapatra et al. [45], highlights the importance of electrode configuration in optimizing production.
5) Integration of sonication into electrolysis: Studies like that of Keboua and Merabet [49] show that integrating sonication into the electrolysis process can improve hydrogen production rates. This suggests that future experimental setups could benefit from incorporating ultrasonic waves into traditional electrolysis setups to enhance overall efficiency and productivity.

6. Sonohydrogen production from potential applications to challenges

Sonohydrogen is a relatively new method with the potential to

Table 5
A comparison of different experimental setups.

Ref.	Freq. (kHz)	Liq. Temp.	Power		Reactor Size (ml)	Efficiency/Production Rate	Probes
			Electric Power (W)	Acoustic Intensity (W/cm^2)			
Petrier & Francony [38]	20 200 500 800	20 °C	30	–	300	The production rate of hydrogen peroxide (H_2O_2), was recorded at 0.7 μmol/min for a frequency of 20 kHz and demonstrated a significant increase to 5 μmol/min at a frequency of 200 kHz.	–
Jiang et al. [39]	20 200 500 800	40 °C	30	–	250	The production rate of hydrogen peroxide (H_2O_2), expressed in μmol/min, registered at 1.1 for an ultrasonic frequency of 20 kHz, and increased to 5.2 at a frequency of 200 kHz.	–
Merouani et al. [40]	from 213 to 1100	–	–	1 W/cm^2	–	The production rate of hydrogen peroxide (H_2O_2), measured in μmol/min, was observed to be 2.1 at a frequency of 1140 kHz, and 4.2 at 585 kHz.	–
McMurray et al. [51]	20	30 °C	–	26	–	–	A titanium sonotrode with diameter of 10 mm
Mizukoshi et al. [44]	200	5–50 °C	–	6 W/cm^2	38 mL	–	A barium titanate oscillator of 65 mm diameter.
Mohapatra et al. [45]	42	22–25 °C	100	–	300	–	An anodization process was conducted using a setup involving two electrodes. The cathode in this configuration was a platinum (Pt) electrode with a flag shape, measuring 1 mm in thickness and having an area of 3.75 cm_2.
Zadeh [46]	20	–	–	–	1000	The study found that the application of ultrasound enhanced the production efficiency by 4.5% and increased the energy efficiency by 1.3%. 82.5%.	The ultrasonic transducer utilized in the study was a Sonics Ti Alloy, with a diameter of 47 mm. It was connected to a Vibracell Sonics VCX750 set at a frequency of 20 kHz.
Kerboua and Merabet [49]	40		60	–	300	average improvement in the hydrogen production rate of 3.93% when sonication is integrated into the electrolysis process.	–
Shestakova et al. [48]	381 863 992 1176	20	250	–	40–7000	–	The ultrasonic transducer used in the experiment was a type E/805/TM with a diameter of 75 mm. It was specifically designed to fit into a jacketed glass reactor.
Ji et al. [43]	20 100 362	18		–	250	–	–
Singh and Sinha [50]	20	299 K	10–40	–	250	–	The PZT transducer ultrasound generator was used to produce ultrasound waves at a frequency of 20 kHz, with adjustable input powers ranging from 10 to 40 W.
Pham et al. [47]	40	25–45	–	38 W/L	20	–	–
Choi et al. [73]	300	20	77.2	–	220	H_2 generation rate increased with specific alcohol concentrations; highest for methanol at 5% (5.46 μmol/min)	–
Merabet and Kerboua [74]	40	27, 40, 45, 50, 55 and 60	60	–	300–350	Efficiency and kinetics of hydrogen production improved with sonication, especially in continuous mode	Stainless steel 304, Nickel, Nickel foam, Graphite

become an efficient source of hydrogen production. In the following sections, we will explore the potential and challenges associated with this innovative approach.

6.1. Potential applications of sonohydrogen production

Various methods may be employed to produce hydrogen. For instance, thermochemical processes utilize chemical reactions and heat to extract hydrogen from organic substances, such as fossil fuels and biomass, as well as from materials like water [75,76]. Sonohydrogen is one of the popular techniques which uses ultrasound waves to facilitate the production of hydrogen. However, it is important to assess the advantages and disadvantages of sonohydrogen production.

Sonohydrogen is an environmentally friendly source of energy that can be used in different industries, such as transportation, power generation, and chemical manufacturing. Using sonohydrogen has several advantages, such as lower energy consumption, higher production rates, and higher purity levels. One of the advantages of sonohydrogen production is its low energy consumption [23]. It requires less energy compared to conventional hydrogen production methods, making it more efficient. Moreover, the process can be easily scaled down or up depending on the specific requirements of the hydrogen production system. Additionally, sonohydrogen production is highly selective, dissociating only water molecules into hydrogen and oxygen without generating any byproducts. Another advantage of sonohydrogen production is its low environmental impact. Traditional hydrogen production methods release significant amounts of greenhouse gases and other harmful pollutants. In contrast, sonohydrogen production does not generate any pollutants and is environmentally friendly, positioning it as a potential alternative for hydrogen production. The potential for higher efficiency is another significant advantage of sonohydrogen production. The intense pressures and temperatures created during cavitation enable rapid and efficient hydrogen generation. Furthermore, the process requires lower energy inputs, reducing overall energy consumption. Sonohydrogen production stands out for its high reaction rates, low energy requirements, and absence of greenhouse gas emissions, making it an environmentally friendly and sustainable method for hydrogen production.

The transportation industry is a significant consumer of fuel, predominantly relying on fossil fuels as its primary source. The burning of liquid fuels for transportation and heating accounts for approximately two-thirds of total greenhouse gas emissions. Despite improvements in efficiency, it is probable that the achievement of future carbon emission reduction targets will necessitate the utilization of low or zero carbon fuels. In this regard, hydrogen fuel cells have the ability to propel electric automobiles, providing an emission free option to conventional gasoline driven engines. As governments worldwide are increasingly prioritizing the reduction of greenhouse gas emissions, hydrogen-powered vehicles have emerged as a promising solution. The use of sonohydrogen production could propose a more cost effective and sustainable method for producing the hydrogen needed to power these vehicles.

Besides being used for transportation, sonohydrogen has the potential to be applied in power generation. While hydrocarbon-based fuels currently play a key role in generating electricity, their increasing costs and negative environmental impact when burned necessitate improvements in the energy conversion efficiency of hydrocarbon-fueled power generation systems. Fuel cells (FCs) are recognized as highly efficient devices for energy conversion, surpassing conventional power generators like internal combustion engines, diesel engines, and turbines.

Another potential application of sonohydrogen production is in chemical manufacturing. Various industrial processes utilize hydrogen as a raw material, such as the manufacturing of chemicals like ammonia and methanol. Sonohydrogen production could offer a more efficient and cost-effective method for producing the hydrogen needed for these processes.

Furthermore, sonohydrogen production has the potential to be used in other applications, such as in the production of electronic and semiconductor materials, as well as in food and beverage processing. In these industries, high-purity hydrogen is often required, and sonohydrogen production can offer a method for producing this type of hydrogen.

In addition, recent studies have focused on optimizing the operational parameters of sonohydrogen production systems. Parameters such as frequency, power intensity, and temperature are identified as critical factors that affect the efficiency and yield of hydrogen production [77]. Studies have employed statistical optimization techniques such as artificial neural networks (ANN) and response surface methodology (RSM) to optimize these parameters and improve the performance of sonohydrogen production systems. Finally, advances in the field of sonochemistry have also contributed to the development of new sonohydrogen production technologies.

6.2. Challenges of sonohydrogen production

Sonohydrogen production has shown great potential as a green and sustainable technology for hydrogen production. However, several challenges need to be addressed before this technology can be commercially viable. One of the key challenges is the high energy consumption of the process, which can make it less cost-effective compared to other hydrogen production methods. Therefore, the development of more efficient and cost-effective ultrasound generators and reactors is needed to decrease energy usage and enhance the effectiveness of the procedure.

Another challenge is the scalability of the process. The current laboratory-scale experiments need to be scaled up to industrial level to meet the hydrogen demand. The design and engineering of large-scale sonohydrogen production plants require careful consideration of several factors such as reactor geometry, ultrasound generator type, catalyst loading, and mass transfer rates. Moreover, the durability and stability of the catalysts used in the process need to be improved to ensure a longer lifespan and consistent hydrogen production over time. The identification and synthesis of more effective catalysts for the process is crucial to enhance the process efficiency.

In addition, the environmental impact of sonohydrogen production needs to be evaluated. While it is a green and sustainable technology, the use of certain chemicals in the process may have adverse effects on the environment. Therefore, a life cycle assessment of the process is essential to assess its environmental impact and optimize its sustainability. Furthermore, the integration of sonohydrogen production with other renewable energy sources such as wind and solar can enhance the overall efficiency and sustainability of the hydrogen production process.

In summary, sonohydrogen applications span across various industries, including transportation, power generation, and chemical manufacturing, showcasing its versatility and the broad scope for renewable energy solutions. However, the path to commercial viability is challenged by factors such as high initial energy requirements, scalability issues, and the need for advanced catalysts and reactor designs. Addressing these challenges through technological advancements and optimization of operational parameters is critical for realizing the full potential of sonohydrogen as a sustainable and efficient hydrogen production method. Future research and development efforts are essential in overcoming these hurdles, potentially paving the way for sonohydrogen to play a pivotal role in the transition towards cleaner energy sources and in achieving global carbon reduction targets.

7. Conclusions

This review paper examines the potential of ultrasound in energy-efficient and eco-friendly production techniques. It focuses on the application of ultrasound in chemical reactions, for hydrogen production and water treatment. The paper has multiple goals as listed below.

- To discuss the mechanisms and techniques involved in the generation and detection of cavitation bubbles caused by utilizing ultrasound generators.
- To provide an overview of various experimental setups and applications that utilize ultrasound technology for hydrogen production.
- To compare the different experimental setups using ultrasound.
- To specifically review the potential application of sonohydrogen.

The key mechanisms and techniques in sonohydrogen production revolve around the utilization of ultrasound to stimulate the production of hydrogen through acoustic cavitation. Parameters such as acoustic intensity, liquid temperature, and frequency are identified as crucial factors that significantly influence the efficiency and yield of hydrogen production. The interaction of these parameters with bubble temperature and the number of moles of H_2 produced is analyzed, providing insights into optimizing the sonohydrogen production process.

A comparative analysis of various experimental setups has illuminated the range of objectives, frequencies, liquid temperatures, and other variables employed in different studies. The analysis has revealed that while the core focus has generally been on optimizing hydrogen production, the setups have also been deployed for diverse objectives such as soil remediation and water treatment. The wide variance in acoustic intensity, frequency, and vessel size among the setups suggests that there is no one-size-fits-all approach, further emphasizing the importance of understanding the underlying parameters for optimizing hydrogen production.

The use of ultrasound waves to enhance the hydrogen production rate and yield has shown great potential in laboratory-scale experiments. Nevertheless, additional investigation is required to enhance the procedure and upscale it for usage in industrial settings.

The analysis of existing research indicates that sonohydrogen is currently being tested in experimental settings, yet it possesses considerable promise as an energy resource. Consequently, we explored the possible uses and obstacles connected to the production of sonohydrogen in this particular context. Despite challenges such as the high cost of ultrasound equipment and the need for efficient catalysts, the benefits of sonohydrogen production make it a promising area for future research and development. With continued innovation and investment, sonohydrogen production has the potential to become a significant participant in the movement towards an environmentally friendly and low-emission energy future.

8. Further studies

While this review comprehensively covers the mechanisms, techniques, and potential applications of sonohydrogen production, several avenues for further research are evident. Some of these include:

- Detailed Life-Cycle Assessment: A more thorough life-cycle assessment of sonohydrogen production can provide insights into its long-term sustainability and environmental impact.
- Material Sciences: Investigating new materials for transducers and probes can contribute to the development of more efficient sonohydrogen production systems.
- Optimization Algorithms: Advanced optimization algorithms can be used to find the ideal wavelength operational parameters for sonohydrogen production, potentially improving efficiency and reducing costs.
- Integration with Renewable Energy Sources: Future studies could explore how sonohydrogen production can be integrated with other renewable energy systems, such as solar and wind, to create a more sustainable energy landscape.
- Industrial-Scale Trials: Most existing studies are conducted on a laboratory scale. Industrial-scale trials are necessary to assess the commercial viability of sonohydrogen production.
- Economic Analysis: A detailed economic analysis, including a comparison with other methods of hydrogen production, will provide more context for the commercial viability of sonohydrogen production.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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